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**EFFECT OF CROP MANAGEMENT FACTORS ON YIELD
OF MAIZE (*Zea mays* L.) HYBRIDS**

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2021

**EFFECT OF CROP MANAGEMENT FACTORS ON YIELD
OF MAIZE (*Zea mays* L.) HYBRIDS**

Dissertation submitted in partial fulfillment of the requirements for the doctoral (PhD)
degree in agricultural sciences

Written by Bramdeo Karamchand (MSc. Agricultural Engineering)

Prepared in the framework of **Kálmán Kerpely doctoral** school of the University of
Debrecen

(Crop production and horticulture program)

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The official opponents of the dissertation:

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The date of the dissertation defence: 20...

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1. INTRODUCTION

Central to the challenges confronting agriculture in the 21st century is the sustainability of food production to satisfy the needs of a growing global population (estimated to reach 9.7 B by 2050) (Fróna et al., 2019; Tilman et al., 2011). Constrained by declining arable land per capita (fig. 1) and changing climatic conditions, alleviating the problem of food insecurity warrants expeditious improvement in agricultural efficiencies, which can increase land productivity (biomass per unit area) and sustain yield, both under favorable, as well as, unfavorable agroecological conditions (Pepó & Csajbók, 2013).

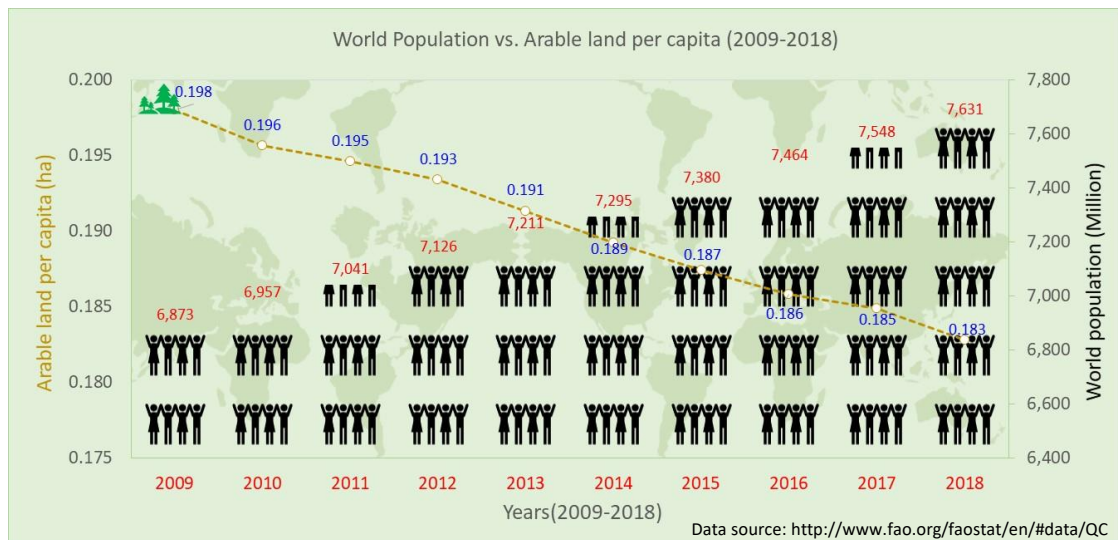


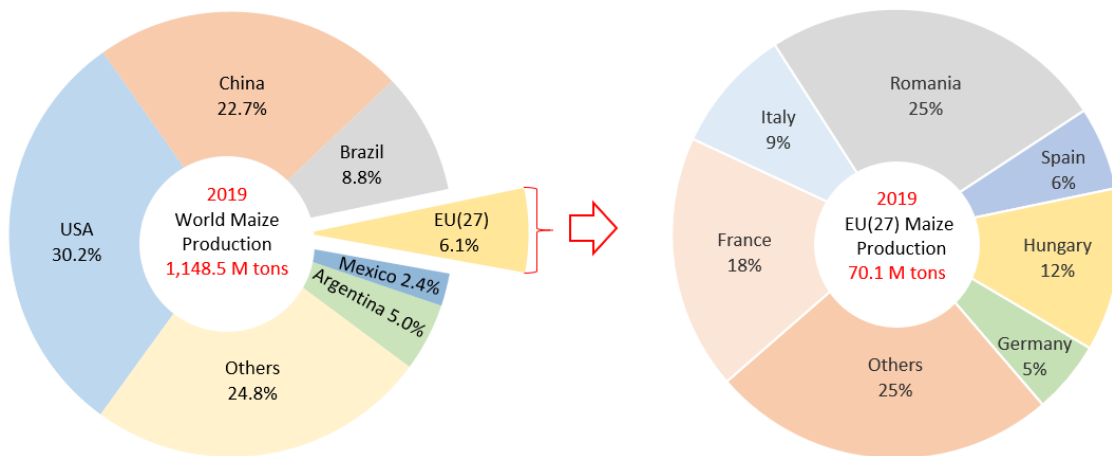
Figure 1. World population vs. arable land per capita (2009-2018)

The urge to increase crop production in many countries has resulted in an intensification of farming practices that utilize high levels of inputs, such as water supply (irrigation), inorganic fertilizers and synthetic chemicals for weed and pest control (Oldfield et al., 2019). These practices have negatively impacted on the environment, resulting in degradation of soil and groundwater quality, thus prompting initiatives for sustainable intensification farming practices which are economically viable and environmentally sound (Liliane & Charles, 2020). This modern approach to intensive farming allows for more efficient management practices which could substantially lower the excessive use of chemicals to the actual requirements of the crop (Tilman et al., 2011) but requires substantial knowledge and expertise to alleviate the disadvantages associated with intensive farming practices (Birkás et al., 2012).

Cereals are among the most essential food crops for human survival, covering almost 52% (728 M ha) of global arable land area (FAO STATS 2020). Compared to other food class, cereals furnish more nourishment and supply almost half of the total energy requirements (Ranum et al., 2014).

Maize (*Zea mays* L.), commonly referred to as corn, is among the primary and most extensively cultivated cereals. It is often referred to as the “Queen” of cereals owing to its high productivity and superior yield potential (Dass et al., 2012). Due to its multipurpose nature, the integration of maize into global agriculture has rapidly increased over the years, with approximately 197 M ha of the crop cultivated across 170 countries (FAO STATS 2020).

Global maize production in 2019 was 1.1 B tons, compared to wheat and rice with 766 and 504 M tons respectively, (FAO STATS 2020). The major maize producing countries are the United States of America, China and Brazil which accounted for approximately two-thirds of global production. The EU-27 contribution is about 6% (fig. 2) of which Hungary’s share is significant and ranks third (12%), after Romania (25%) and France (18%).



Source: FAO Stats 2020

Figure 2. World major maize producing countries(left) & EU major producers (right).

Maize is a dominant grain crop in Hungary, occupying approximately 40% (1M ha) of the total cereal production area. The mean sowing area over the last decade (2009-2019) varied between 1.20 and 0.96 M ha (25%), whereas, yield fluctuation has been substantial (115%), ranging from 4.0 to 8.6 tons ha⁻¹, mainly due to unfavorable climatic conditions (Fertő & Szerb, 2017). Although average yield over the last five years has

shown significant improvement, compared to the other major maize producing countries within the EU, Hungary's yield remains relatively low and leads only Romania and once surpassed France in 2016 and Germany in 2019 (fig. 3). The significant fluctuation and relatively low yield of maize in Hungary provide scope for improvement.

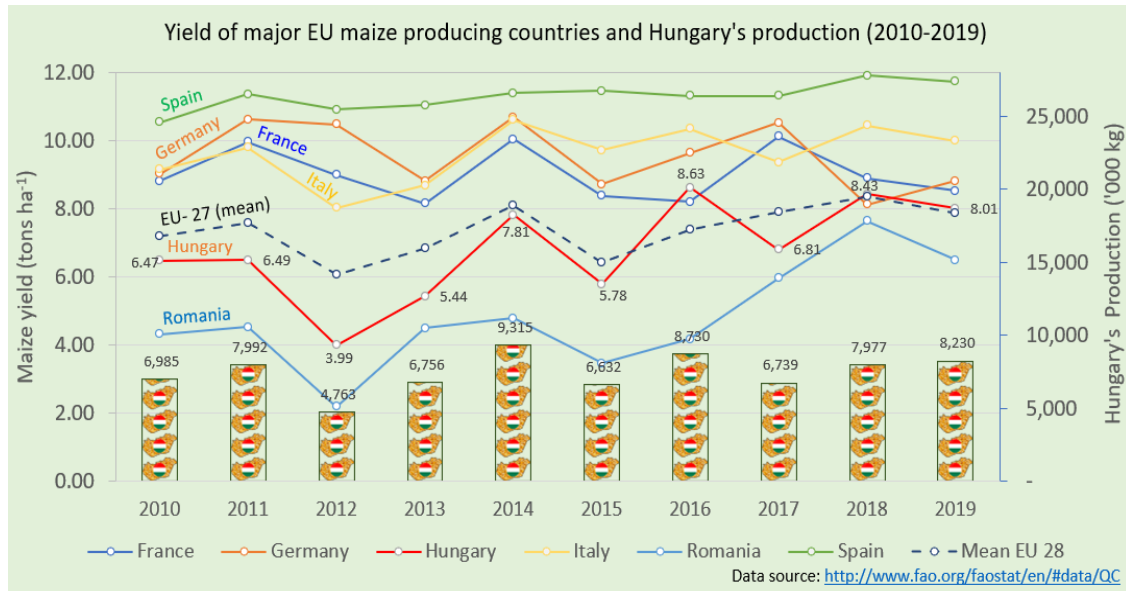


Figure 3. Hungary's maize production and yield compared to main EU producers

Challenged by the dynamics of the weather conditions and need for protection of the environment; reducing fluctuation and achieving high and stable yield is no easy feat. It requires innovation and continuous evaluation of crop production technologies to identify the most appropriate levels of agrotechnical inputs and best practices which can be implemented to optimize and sustain the yield of a particular genotype under a given set of agroecological conditions.

Yield, which is basically the productivity of a plant, is influenced by a combination of factors, grouped into three main categories, which comprised the agroecological (e.g. climate, soil, topography), agrotechnological (e.g. farming practices such as tillage systems, nutrient supply, irrigation, sowing technology, crop rotation, plant protection, harvest) and the biological (genotype) factors. These factors do not act in isolation but interact with each other and thus, it is the level of interaction among these factors which determines the final yield. Harmonization of these factors (agroecological and agrotechnological) with the needs of the genotype is therefore fundamental for achieving high and stable yield (Berényi et al., 2007; Pepó & Csajbók, 2013).

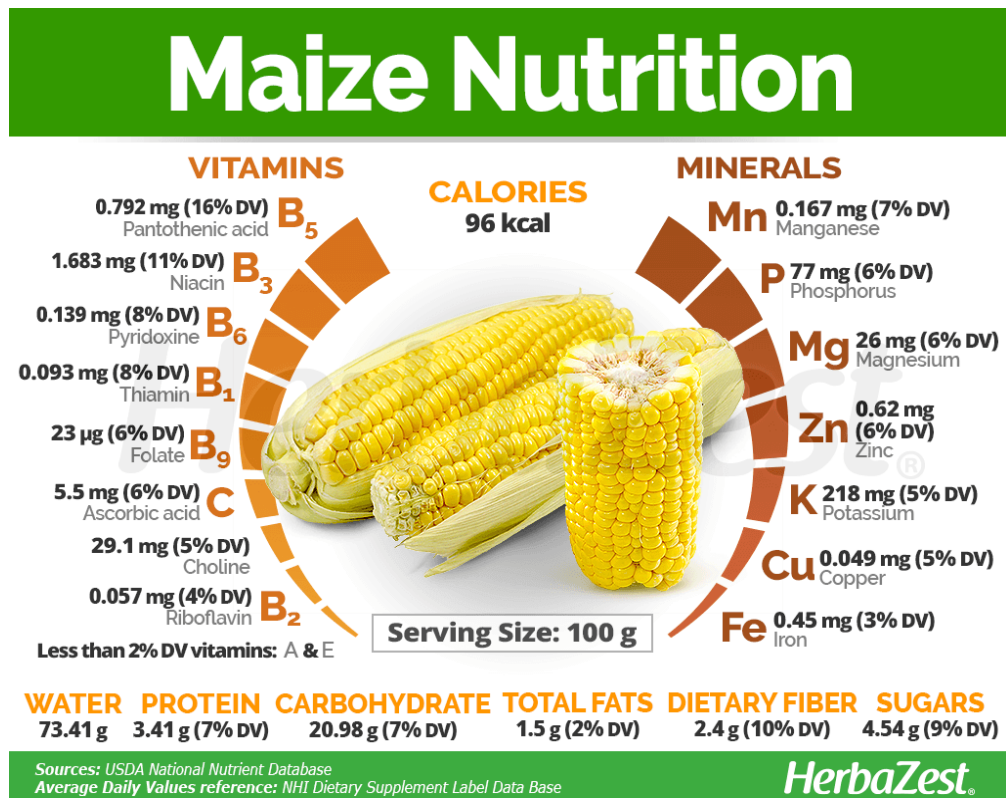
Tillage practices, irrigation, fertilization, plant population density and crop rotation are all integral agronomic management factors which have significant influence on yield and impact to varying extent on the environment. The magnitude of the effect of these crop management factors on yield is strongly modified by weather condition of the prevailing crop-year, mainly because of variability in precipitation amount, distribution and temperature (Nagy, 2007).

The extent of yield-losses and yield fluctuation caused by adverse weather depends on soil condition, the stress-tolerance of genotypes and the agronomic management factors. The latter provides greater flexibility for manipulation and therefore its optimization can help mitigate against harmful climatic effect (Pepó, 2012). The prerequisite, however, is a thorough understanding of the dynamics of the interaction among the agroecological, agrotechnological and biological factors, as it is paramount for enabling harmonization and optimization. Thus, the need for ongoing evaluation (research).

The sustainability of crop production technologies and the impact of climate variable on yield is best studied in long-term experiments (Berzsenyi et al., 2011). Established in 1989 at the behest of Béla Györfy and pioneered by Professor Dr. János Nagy of the University of Debrecen, this long-term experiment provides the medium for investigating the impact of tillage practices, fertilization, plant density, forecrop (winter wheat) and irrigation on maize yield under varying climatic conditions (long-term). Thus, this research is part of an ongoing long-term multifactorial experiment, aimed at evaluating various levels of agrotechnical inputs under different climatic conditions of the examined crop-years (2018-2020) and to determine the treatment combination that will deliver the best results over the examined period, taking into consideration economic feasibility and environmental sustainability.

1.1 Economic importance of maize

Maize is popular as a multipurpose crop. In addition to being a superb feed and low-cost energy source for livestock, it also supplies base material for numerous industrial processes (Nagy, 2006). As a major energy source in the diet of livestock, maize provides a high level of carbohydrates, and fair amounts of dietary fiber and plant-based protein, as well as minerals, such as magnesium, phosphorus, potassium, zinc, copper, and manganese (fig. 4).



Source: <https://www.herbazest.com/herbs/maize>

Figure 4. Maize nutritional content

World production over the last decade has significantly increased (34%) from 820 M tons in 2009 to 1.1 B tons in 2019 (FAO STATS 2020). Maize is a staple food in many countries around the world and the basis for food security to more than 1.2 billion people. Maize provides approximately 33% of the caloric consumption in Latin America, the Caribbean and African continent (FAO STATS 2020). The majority of maize produced in developed countries (80%-90%) is utilized for animal feed, whereas, in under-developed and developing countries, besides being a staple food, it is a means of sustenance for many poor farmers (Shiferaw et al., 2011). Maize is also a source of several phytochemicals such as, phytosterols, phenolic acids, carotenoids, and flavonoids (Lopez-Martinez et al., 2009; Shah et al., 2016).

Maize kernel contains an estimated 72% carbohydrates, mainly as starch, while protein and fat average at 10% and 4% respectively. It supplies an average of 365 Kcal per 100 g of kernel and can be consumed in a variety of ways (off the cob, parched, roasted, boiled) or ground and utilized for bread, porridge, gruel and cakes (Ranum et al., 2014; Nuss & Tanumihardjo, 2010). Maize grains can also be processed into numerous products, such as, corn starch, syrup, sweeteners, beverages, corn oil, glue, ethanol and biofuel. Based on the nutritional and energy value the grains, it is estimated that one hectare of maize is capable of supporting the production of 15,000 liters of milk, 2000-kg beef or 3,000 kg of pork, while corn-cob mix made from 1 ha maize, complete with protein and minerals can adequately rear 35-40 pigs (Nagy, 2006).

Maize contribution to the Hungarian Agricultural and Food Sector is significant. It contributes to investment, land use, gross value added, employment and export earnings (trade). Maize is considered as one of the most important agricultural export products in Hungary (Fertő & Szerb, 2017). According to the Ministry of Agriculture (MoA) information bulletin (2019), Hungary's contribution to the EU is substantial and now ranked as the third largest maize producer behind France and Romania. Annual production over the last decade (2009-2019), fluctuated between 4.7 to 9.3 M tons (KSH 2020), of which 3.5-4.0 million tons was utilized for domestic consumption, while the remaining amount was exported, mainly to Italy, Romania, the Netherlands, Germany and Austria (Fertő & Szerb, 2017).

In 2018 Hungary's share in EU agricultural output for maize was 11.5% and income from export earnings was the highest among the cereals (649.3 M €), (KSH 2020). The majority (90%) of the maize produced in Hungary is used as fodder, while the remaining fraction is utilized for human consumption (3%), seed (0.5%) and production of alcohol (1%), starch and sugar (6%).

Maize is cultivated on approximately 25% of arable land areas in Hungary, compared to 14% globally and its multipurpose and expanding usages will continue to be of great significance to the Hungarian economy and the world at large.

1.2 Aim of research

This research aims at determining the best treatment combination of agronomic management practices (tillage, fertilization, planting density, crop rotation, irrigation) which will optimize yield of maize hybrids, considering economic viability and environmental sustainability.

The objectives are as follows:

- (a) Determine the most efficient level of fertilization (N0, N80, N160 kg ha⁻¹) for optimum yield and least environmental consequences.
- (b) Determine the best of three tillage practices (Mouldboard tillage (MT); Strip tillage (ST); Ripper tillage (RT) which optimizes yield.
- (c) Determine the most appropriate planting density (60,000 versus 80,000 plants ha⁻¹) for the test hybrids (FAO 490, FAO 420, FAO 380).
- (d) Determine the extent to which crop rotation (winter wheat forecrop) influences the yield of maize hybrids.
- (e) Assess the impact of irrigation on the yield of the test hybrids and identify any drought resistance potential.
- (f) Determine the extent to which crop-year x agrotechnology interaction influences yield of the test hybrids during the examined period.
- (g) Determine the extent to which agrotechnical inputs influence the starch, oil and protein content of the maize kernel.
- (h) Identify the treatment combination which will deliver the best results.

The findings of this study will complement the knowledge-base, garnered from similar research and function as an effective management tool in the selection of the most appropriate crop production model with the aim of reducing fluctuation, optimizing yield and achieving production sustainability of maize in Hungary.

2. LITERATURE REVIEW

2.1 Maize Origin and Distribution

Maize (*Zea mays*), is a monoecious plant, belonging to the family Poaceae (Gramineae). According to Kumar & Jhariya (2013), the word “Zea” is Greek in origin and means “sustaining life” while “Mays” originated from the Taino language and meant “life giver”. It is believed to have originated from its wild relative teosinte between 7,000-10,000 years ago in the Balsas River Valley in South-western Mexico. As a result of many changes through a combination of genetic mutation and human selection, teosinte has evolved into cultivated maize (Ranum et al., 2014).

Maize was first introduced into Europe in 1493 by Christopher Columbus and initially grown mainly in the Mediterranean countries, then later spread to Hungary, both from Italy and Turkey at the beginning of the 16th-17th centuries. By the 19th century maize was cultivated in nearly all regions of Hungary (Pepó & Csajbók, 2013).

2.1.1 Types of maize

According to George Dickerson of New Mexico State University, among the cereal crops, maize is the most diverse and both natural and human selections have produced corn of various types, which can be classified based on the endosperm of their kernel. The most popular types include pop, flint, dent, flour and sweet (fig. 5).



Figure 5. Types of maize kernels.

(source: https://aces.nmsu.edu/pubs/_h/H232/welcome.html)

Among the different types, dent corn is produced in the largest quantity in the major maize producing countries (Sciencedirect.com) and is utilized mainly for fodder, while the other corns are produced for special aims. The three test hybrids in this study (Armagnac-FAO 490; Loupiac-FAO 380; Fornad-FAO 420) are of the dent corn type.

2.2 AGROECOLOGICAL FACTORS IN MAIZE PRODUCTION

Maize is a plant of tropical origin but has evolved through decades of breeding to produce hybrids with a wide range of adaptability (Edmeades et al., 2017). Maize belongs to the group of C4 plants, which is more efficient due to photorespiration and rapid transport of assimilates (Hatfield & Dold, 2018; Pepó & Csajbók, 2013).

The response of the maize plant to climate depends on the physiological makeup of the hybrid and the duration for the hybrid to reach maturity is dependent upon the geographic location, sowing date, and the weather condition during the cropping season (Ross et al., 1996). According to Dobos & Megyes (2013), the latitude for realizing the highest yield potential of maize is 42-45° worldwide, while the climatic conditions in Hungary is suitable for production of hybrids without high risk until FAO 500-600. The demands of the maize plant regarding heat and humidity are relatively high and its geographic range is determined mainly by temperature, but within the region of favorable mean temperatures, the precipitation during the growing season is decisive (Nagy, 2006).

It is the kernel number and individual kernel weight, which determines maize yield and are highly influenced by weather conditions. Even though the biological base has significant influence on kernel composition and final grain yield, the temperature and moisture availability during the growing season also plays an important role, especially during key physiological phases (Butts-Wilmsmeyer et al., 2019).

2.2.1 Precipitation

Inadequate water to meet the needs of the crop, as well as, water supply in excess of the needs of the crop constitutes severe stresses which impacts negatively on growth and development and are likely to intensify with climate change (Martinez-Feria & Basso, 2020). Among the weather variables, rainfall amount and distribution during the cropping period are especially important. As a result of differences in the quantity and distribution of rainfall during the cropping season, the effects of the year on growth and yield parameters of maize are frequently observed in long-term experiments (Pepó et al., 2007; Nagy, 2006; Boomsma et al., 2010).

In favourable crop-years with adequate rainfall, maize yield is usually higher, while in droughty years, yield is adversely affected, resulting in significant fluctuation (Bramdeo

& Rátonyi, 2020; Huzsvai & Nagy, 2005). Maize yield is closely correlated with precipitation of the winter period and growing season. Hence, in years with high levels of rainfall, fertilizer utilization is better, resulting in greater yield increasing effect (Nagy, 2003).

The growing period of maize in Hungary is from April to September and the length of the season is altered mainly by temperature and the semi-arid climatic condition is the most important limitation to maize production, due to low precipitation during the summer. Following emergence, maize average daily water usage increases from 2 mm to approximately 9 mm during the flowering and early grain-filling stages. The highest water consumption period ranged from mid-June to mid-August. Maize requires 550 - 670 mm of water per growing season for optimal growth and the most critical periods for water supply is flowering and early grain formation (Pepó & Sárvári, 2013; Nagy, 2006).

Several researchers have found a very strong correlation between July rainfall and maize yield and attributed it to the critical phenological phase of the crop in July. A dry July affects the development of cobs with resulting low yield, while yields are generally high after a rainy July and August (Nagy, 2006). Data from long-term experiments have demonstrated that among the months of the growing season, July rainfall had the strongest correlation with yield and moisture deficit at this time can significantly affect yield. The risk associated with July drought can be minimized with earlier sowing and significantly lower grain moisture can also be achieved, due to early ripening and harvesting (Dobos & Megyes, 2013).

Sah et al. (2020) reported that yield loss as a result of moisture deficit stress in maize at flowering and grain-filling stage, ranged from 34.28 to 66.15% for non-drought tolerant and 38.48 to 55.95% for drought tolerant lines. According to Singh et al. (2007) water deficit stress was found to reduce growth and development and delay initiation of flowering in maize. While several studies have confirmed moisture deficit at flowering and grain filling was most critical, a study conducted in China between 2013-2016 by Song & Jin (2019), found extreme moisture deficit at the early emergence stage of maize was more detrimental to growth than moisture deficit stress during jointing, heading, and grain-filling, since it results in reduction of photosynthetic area (LAI) and biological yield, due to decline in interception and efficiency use of active radiation

(photosynthetic) which extends to the flowering stage and subsequently reduced grain yield.

Nagy (2007) reported that higher yields were always associated with high levels of rainfall, but low yield was not always as a result of the least rainfall. In Hungary, water supply during the reproductive phase (flowering & fertilization), i.e. from 15th July to 15th August is considered to be most crucial, since moisture deficit at this time can adversely affect yield.

Zdeněk et al. (2017) evaluated several water supply indicators to establish which had the strongest correlation with the yield of maize. The indicators included monthly precipitation, average soil moisture at various depths, evapotranspiration, sum of effective global radiation and average drought intensity, etc. They found that in all years, the most important month for rain-fed irrigation was July, followed by August as the second most important month and precipitation accounted for 64% of the yield variability. Similarly, Huzsvai & Nagy (2005) found that yield fluctuation of maize is mainly determined by the available soil moisture in July and May water supplies.

2.2.2 Temperature

In addition to precipitation, temperature is also an important climatic factor affecting maize production (Lobell & Burke, 2008). According to Kenny & Harrison (1992), the main climatic limitations to grain maize production in Europe, are the effects of water supply on growth and temperature on development. They found that an increase in temperature (+2 °C) negatively impacted on the water balance output and an increase in precipitation (+10%) can compensate for the negative effect.

Unlike rainfall, which has a linear effect on yields, temperature has a non-linear effect and is most important from planting to tasseling since it influences germination and absorption of nutrients required for growth and development (Santos et al., 2019; Mera et al., 2006). According to Nagy (2006), under Hungarian condition, the length of the growing period is altered mainly by temperatures between germination and appearance of tassels. Drastic changes in temperature can significantly affect the germination of maize owing to the sensitivity of hormones and enzymes to changes in temperature.

Extreme temperature also increases water loss (evaporation) and reduce available moisture which can impact adversely on germination.

Heat units are required for physiological functioning of the plant and would vary depending on the growth stage. According to Theivasigamani et al. (2013), growing degree days (GDDs) are useful for assessing a region suitability for a specific crop, predicting physiological maturity for a crop and harvest dates as well as the best timing for agronomic inputs. Based on research in Iowa, maize usually requires, 90 - 120 GDDs from planting to emergence with adequate soil moisture. The GDD will vary depending on location, planting depth, tillage system, and soil residue cover. Butts-Wilmsmeyer et al. (2019) found the GDD had the strongest correlation with temperature during grain filling stage. They reported correlation between GDD and mean temperature during early growth stage was $r = 0.52$, compared to $r = 0.70$, during grain filling.

Maize has an assimilation heat threshold of 10°C and needs 1100-1450°C useful heat sum during its vegetation period. Temperature is considered most important during the first part of the growing season, from planting until flowering. The maize plant growth is inactive at temperatures lower than 50°F (10°C) and higher than 86°F (30°C). The optimal soil temperature during sowing and germination is 10°C and the highest yields of maize can be realized where the average temperature of the summer months range between 21-27 °C. The ability of maize to germinate at high temperature (>37° C) is related to the temperature sensitivity of the embryo, which is also dependent on the genotypic traits (Dobos & Megyes, 2013).

Temperature for optimal vegetative growth, ranges from 18-20°C, while from flowering to yellow ripening, 24-26°C is considered to be favorable. Maize is sensitive to high temperature above 30°C during flowering (July) and the effect of high temperature is exacerbated by moisture stress, which can result in reduction in fertilization and grain development processes. The critical phenological phase of the maize plant in July and the increased sensitivity to high temperature and moisture stress, therefore, explain the reason for the strongest correlation between July rainfall (positive) and temperature (negative) with yield (Pepó & Csajbók, 2013).

Southworth et al. (2000) reported that high temperatures, especially during silking (tasseling) resulted in significant yield decreases. According to Hatfield & Prueger (2015), maize is most sensitive to extreme temperature during pollination and

unfavorable temperature can result in reduction of grain yield of maize by as much as 80–90%. Cheikh & Jones (1994) reported that heat stress caused by temperature extreme during the early stage of kernel formation leads to abortion or premature cessation of growth and found that 23% kernels were aborted with four days of heat stress at 35 °C, three days after pollination, whereas, 97% of kernels were aborted at 35 °C, over an eight-day period. Shim et al. (2017) found that yield reduction as a result of increased temperature during the reproductive phase is due mainly to decrease in kernel number rather than decrease in individual kernel weight. Similar report by Lizaso et al. (2018) showed that maize yield decreased with heat stress primarily through loss of pollen viability, which affects the number of kernels. Hatfield & Prueger (2015), concluded that higher temperature exhibits greater impact on grain yield rather than on vegetative growth and since the effect of temperature influences soil water status, reduction in rainfall along with high temperatures would amplify the negative impact on grain yield. Sunoj et al. (2016), found that lower diurnal temperature amplitude increased the respiration rate of leaf at night, resulting in a decrease in carbohydrate content and subsequent reduction in overall biomass accumulation.

Heat stress is known to significantly reduce maize yield due to its adverse effect on growth and development. Edreira et al. (2014) found that hybrids in temperate region was more prone to heat stress, resulting in grain filling being halted at an earlier stage which corresponds to a depletion of reserve in the stem, compared to tropical hybrids.

Ordóñez et al. (2015) found that an increase in temperature during critical phenological phase can reduced harvest index, from approximately 46% in unheated environment to 20% under elevated temperature and the loss was greater in fertilized plots (N200) compared to non-fertilized treatments. The results revealed that yield reduction in response to increase temperature were amplified by nitrogen availability and suggested that a well-fertilized maize crop may be more prone to heat stresses. Their results concurred with several other research findings which showed that maize yield positively correlates with N fertilization and negatively with heat stress and yield penalty imposed by heat stress was much more pronounced in hybrids with longer cycle, compared to short-cycle hybrids.

2.2.3 Soil requirements of maize

Among the related cereal species, maize is the most demanding regarding the quality of soil and performs best on deeply tilled, medium heavy loam, high in organic matter and nutrient content (Nagy, 2006). In Hungary, chernozem and soils of chernozem-like characteristics are more favourable for maize production.

According to Pepó & Csajbók (2013), maize can also be cultivated successfully on the better quality of brown forest, grassland and silty soils of favourable traits with application of appropriate agro-technique. They reported that maize can also be produced on sandy and sodic soils of weaker abilities but with significantly lower yield. It is important for soil in maize cultivation not only to be favorable in nutrient, water, air and biological activities, but also their culture states have to be favorable (Pepó, 2012). The ideal soil for maize is characterized by adequate aeration, good water balance, a thick fertile layer, warms up easily and has a pH of 6.6-7.5.

2.2.4 Interaction of crop-year and agronomic management factors

Climate influences all aspects of crop production, including crop area and crop intensity (Liliane & Charles, 2020). According to Baum et al. (2019), as a result of variation in weather conditions and less than desired soil conditions in the spring, planting is frequently executed beyond the optimum opportunity time, thus, compromising on yield.

Weather regulates moisture supply and heat in the crop environment, as such, it affects material transformation, fertilizer utilization and nutrient uptake (Nagy, 2007). The impact of climate change on crop production is highly dependent on the geographical location and is very evident with changes in climatic variable such as temperature and precipitation (Ghaffari et al., 2002). Within the European region, the most negatively affected locations were observed in the continental climate of the Pannonian environmental zone, which includes Bulgaria, Hungary, Romania and Serbia (Olsen et al., 2011).

Lobell et al. (2011) reported that climate had significant impact on crop yield and variation in climatic condition accounts for approximately 33% of the observed yield variability.

Water availability during the reproductive and grain filling stages solely determine grain yield and compositional quality. In rainy years, the protein content of maize was found to be lower (-10.8%) than in the dry year (Széles & Nagy, 2012). Similar report by Butts-Wilmsmeyer et al. (2019) revealed in very dry years, grain protein content negatively correlated with maize yield. They noted that in years with average or favourable weather conditions the negative relationship between grain yield and protein content was absent.

Pepó et al. (2008) found in extremely dry year (2007) maize yield was significantly reduced in monoculture, non-irrigated treatments with high fertilizer dosage (N240) and high population (80,000 plants ha⁻¹) and observed very good yields were obtained in year with adequate water-supply and optimum heat units. Berzsenyi & Dang (2003) found in dry condition, lower fertilizer dosage had greater stability, while in favorable years with high rainfall, higher fertilizer dosage enhanced yield stability.

According to Pepó (2007), under favorable conditions, fertilization could generate up to 50% yield increase. However, under excessively dry conditions (drought) it has no yield increasing effect. Wang et al. (2020) also found that Nitrogen fertilization significantly improved maize grain yields by almost 27% in years with high rainfall, but in dry years, yield increment from fertilization did not exceed 6%. Similarly, Széles et al. (2018b) observed maize yield decreased by 16% under drought conditions, while in year with optimum rainfall, yield increased by 19%. The lower yield in dry-crop year and higher yield in wet year is also corroborated by reports of several researchers (Nagy, 2003; Sulyok, 2005; Berzsenyi & Dang, 2004; Árendás et al., 2004).

Bramdeo & Rátonyi (2020a) found that in favorable crop-years with adequate rainfall, maize yield in conventional tillage differs significantly from reduced tillage, while in year with low rainfall, such as 2015, yield differences among tillage systems (strip, ripper and mouldboard tillage) was not statistically significant ($P>0.05$). They reported that year-effect on maize yield was significant and accounted for approximately 21% of the yield variance. In year with low levels of rainfall and higher temperatures, they found that reduced tillage, such as, ripper tillage and strip tillage, lower planting density (60,000 plants ha⁻¹) and lower fertilizer dosage (N80) give optimum results, compared to favorable crop-year where higher planting density of 80,000 plants ha⁻¹, coupled with higher fertilizer dosage (N160) and moldboard tillage deliver the best results.

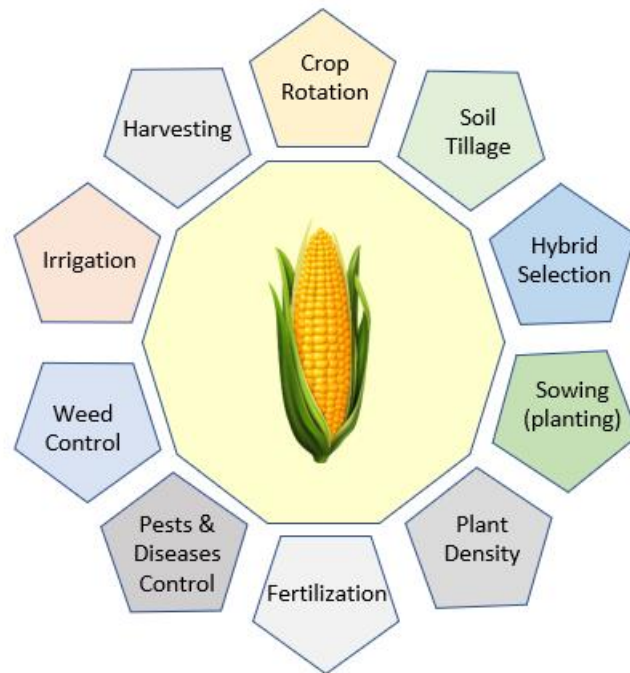
Berzsenyi & Dang (2003) reported that apart from the dominating influence of N-fertilization response of maize hybrids, the interaction between fertilization and hybrids could be ascribed principally to the modifying effect of the crop-year and the different yield levels of the hybrids in the various maturation groupings (FAO). Pepó & Sárvári (2013) found that crop-year effect was most significant in continuous maize (monoculture) and a maximum of 5.8 t ha⁻¹ was obtained in dry crop-year, 9.6 t ha⁻¹ in an average crop-year and 12.8 t ha⁻¹ in wet crop-year with optimum fertilizer dosage. Huynh et al. (2019) also observed significant interactions between tillage, crop rotation and irrigation in crop-years characterised by extremely low rainfall.

In corn-soybean rotation, Wilhelm & Wortmann (2004) found maize yield was more influenced by weather conditions and tillage practices than soybean, and the greater rotational effects on maize yield could be attributed to the cooler weather in spring and warmer conditions of the summers. Similar report by Boomsma et al. (2010), showed that cropping season temperature and rainfall, influenced the effect size of crop rotation and tillage practices on maize yield. Several researchers have observed that weather condition of different years produce large differences in yield for similar levels of agrotechnical input, thus demonstrating the modifying effect of the crop-year.

In drought years, majority of the agronomical inputs have no significant impact on maize yield (Micskei et al., 2009). The amount of precipitation reorients the need and effect of fertilizers, hence, under drought condition the beneficial effect of fertilization is reduced due to increasing N salt concentration in the soil (Debreczeni & Debreczeniné, 1983).

According to Below (2018) “high yield just don’t happen by accident, you have to plan for it, because the factor that has the biggest impact is that year’s weather”.

2.3 AGROTECHNOLOGICAL FACTORS IN MAIZE PRODUCTION



Source: Pepó & Csajbók, 2013, (schematic K. Bramdeo)

Figure 6. Agrotechnological factors in maize production

It is the agrotechnological factors (fig. 6) in conjunction with the biological base and agroecological conditions that determines the final yield and grain quality of maize (Below, 2018; Butts-Wilmsmeyer et al., 2019; Pepó & Csajbók, 2013).

Among the agrotechnological factors, fertilization was found to have the largest impact on yield (Nagy, 1996a; Bramdeo & Rátónyi, 2020; Györfy, 1976). According to Below (2018), corn yield starts with plant nutrition, which sets the trajectory. Pepó & Sárvári (2013) demonstrated that forecrop, fertilization, irrigation, plant population density and weed control are among the most essential agronomic factors in maize production and the weather conditions can significantly modify the level of interactions between the genetic, environmental and agronomic management factors.

Nagy (2006) posited that the majority of agrotechnical intervention are designed not only to increase yield but also to reduce moisture content at the due date of harvesting. In unfavorable year with inadequate moisture, Sárvári & Pepó (2014) observed yield fluctuated in extensive cropping system, compared to favorable year (adequate moisture) in intensive cropping system, where yields were observed to be much more stable. They concluded that optimization of the agronomic management factors can help to mitigate against adverse climatic effect. According to Nagy & Zeke (1981), agrotechnological

inputs influence both the yield of maize, as well as the grain moisture content, hence optimization of these inputs increased yield, and also decreased the grain moisture content at harvest. To achieve this objective, it is essential to establish the optimum level of agrotechnical inputs which takes into consideration the prevailing weather, soil condition and topography of the location, as well as, the specific needs of the hybrid for cultivation (Pepó & Csajbók, 2013).

Among the agrotechnical factors, fertilization was found to have the largest impact on maize yield and accounted for 27-48% yield increase. Györfy (1976) found fertilization increased yield by 27%, variety 26 %, soil cultivation 24 %, plant density 20 % and deep tillage 3 %, while Nagy (1996) reported yield increase from fertilization was 48%, irrigation 28%, soil cultivation 18% and plant population 6 %. Similarly, Bramdeo & Rátonyi (2020) reported fertilization accounted for 35.8% yield variance, crop rotation 12.8%, plant density 3.4%, soil cultivation 1.2% and irrigation, less than.

2.4 TILLAGE

Tillage has played a fundamental role in the revolution of agriculture and crop production (FAO 2020). Tillage entails the physical manipulation of the soil in a range of cultivation operations, to produce seedbeds suitable for growth and development of the crop (Ahn & Hintze, 1990). Essentially, the goals of tillage include preservation of the favorable soil attributes, such as, moisture conservation, soil structure, organic matter content and preventing weed infestation, while alleviating circumstances leading to detrimental processes. This can be achieved by executing tillage operations at the recommended soil moisture content, minimizing trafficking and varying the depth and methods over time (Birkás, 1989; Birkás, 2010; Nagy & Rátonyi, 2013).

Soil manipulation through different tillage practices can significantly change soil fertility status which can impact positively or negatively on the performance of crops (Ohiri & Ezumah, 1990). A change in tillage practices can result in changes in biological, chemical and physical properties of soil and subsequently the functional quality of the soil (Islam et al., 2000). The influence of tillage on soil chemical properties is dependent on the organic matter content of the soil. Tillage accelerates the rate of decomposition of organic matter and hence, biological activities through soil organisms, which influence soil aggregates formation and infiltration rates of water (Iqbal et al., 2013).

Tillage effects which compromise the favorable attributes of the soil include, excessive pulverization and desiccation, compaction and hardpan formation, puddling of soil structure, reduced infiltration rate, accelerated decomposition of organic matter and proliferation of weeds (Birkás, 1989; Nagy & Rátonyi, 2013).

The alteration of soil physical properties such as, bulk density, moisture content, penetration resistance and infiltration rate as a result of different tillage practices, significantly influence germination, cropping intensity, root distribution and yield (Rashidi & Keshavarzpour, 2007; Khan et al., 2017).

According to Laboski et al. (1998), bulk density had significant effect on root growth and extension. Bulk density for optimum crop development for most soils range from 0.9-1.2 t m⁻³. Plant root growth is severely hampered when the bulk density for loam/clay loam soil exceeds 1.3-1.6 t m⁻³ and when it exceeds the range of 1.6-1.8 t m⁻³ in sandy soils (Olness et al., 1998).

Technological advancement in agriculture has led to increase mechanization and intensive tillage operations which are the main causes of increased bulk density (Rashidi & Keshavarzpour, 2007). Soil with high bulk density (compacted) reduces soil porosity and water infiltration, shortens rooting depth in lower soil profile, while enhancing the length of roots in upper layers (Shierlaw & Alston, 1984). Soil compaction substantially influences moisture absorption by the plant roots and in moderately compacted soil, moisture absorption rate was found to be 67% higher than in highly compacted soil (Nosalewicz & Lipiec, 2014). Continuous tillage at same depth with same implement creates hard pan which increases bulk density, decrease infiltration and rooting depth, and protracts flooding in the fields during wet seasons, thus adversely affecting crop growth and ultimately yield (Birkás et al., 1997; Wasaya et al., 2011; Hakansson & Reeder, 1994).

Birkás (1989) found continuous use of shallow disc tilling usually result in low yield due to soil compaction and recommend intermittent application of deep loosening. According to Schneider et al. (2017), the popularity of subsoil tillage declined in the 1970s, presumably because of inconsistent yield responses which could not compensate for the high execution cost. Several researchers have however, reported that the increased yield with deep tillage can compensate for the high costs, especially in soil with root restricting layers.

2.4.1 Tillage systems in maize production

Tillage systems are site-specific and the basic criteria for quality in soil tillage practices hinge on the right choice of equipment, followed by the correct procedures according to the system to be applied, taking into consideration, type and cultural status of the soil, crop to be grown, weather, forecrop, topography and weeds situation (Rasmussen, 1999; Nagy, 2006). Maize requires deep tillage and the quality of tillage is of special significance for the successful establishment of the crop (Pepó & Csajbók, 2013). The sequence of events for tillage operations can be summarized as follows:

Stubble → primary soil tillage → secondary soil tillage → seedbed formation → post-sowing soil preparation (Nagy & Rátonyi, 2013).

According to Nagy (2006), one of the key principles of maize production in Hungary is a tillage system that conserves the most water because growing season rainfall is generally inadequate. Maize is usually sown in the spring (April) and harvested in autumn (October) and soil preparation is accomplished in two phases (autumn cultivation and spring cultivation). After an early harvest of the previous crop, the system follows the procedure outline in fig. 7 a, whereas in a late harvest of the previous crop, the procedure is illustrated in fig. 7b.

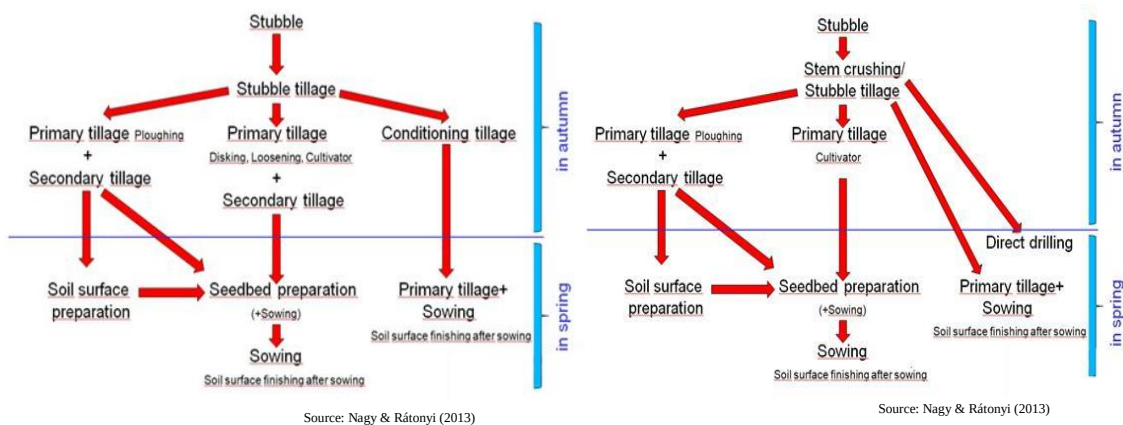


Figure 7a. Tillage sequence for early autumn harvest

Figure 7b. Tillage sequence for late autumn harvest

After the late harvested previous crop, primary tillage is carried out with or without rotation (plowing), combined tillage and sowing or direct drilling (fig. 7b). If autumn primary tillage is not possible, then it can also be carried out in the spring. However, spring plowing is considered to be risky because of moisture loss. Nagy (2006),

demonstrated the capability of autumn plowing to produce generally higher yields over spring plowing and plowless methods in deep loamy soil and concluded the benefits of autumn plowing are 70% in dry conditions and 89% under irrigated conditions. The aim of plowing in autumn is for capturing and storage of water (precipitation).

The sequence of tillage operations commenced with stubble, which is performed immediately after harvesting and involves a shallow disking (max. 10 cm) with the aim of mixing plant residues into the shallow soil, reducing moisture loss, controlling weeds and the heat cycle of the soil and improving the soil biological activity. Primary tillage then follows with the aim to loosen, reduce soil strength and incorporate fertilizers, crop residues, kill weeds, and to aerate the soil. The implements for primary tillage include moldboard plows, chisel plows, disk plows; heavy tandem harrows and subsoilers (deep loosener). Primary tillage is usually deeper than secondary tillage and establishes the most appropriate soil conditions (physical) for the duration of the vegetative period.

Secondary tillage is carried out after the primary tillage to refine the soil in accordance with the needs of the crop. The equipment for secondary tillage, include disc, smoother, roller, cultivator, rotary tiller, rotary harrow, swinging harrow (Nagy & Rátonyi, 2013). Secondary tillage usually operates at shallower depth range compared to primary tillage equipment and provide additional soil pulverization for seedbed formation. (Siemens et al., 1992).

2.4.2 Classification of tillage systems

Soil tillage systems involves the mechanical manipulation of the soil through a sequence of operations to produce seedbeds for the successful establishment and production of one or more plants (Nagy & Rátonyi, 2013).

According to the University of Wisconsin Extension Service, tillage systems can be classified as either conventional (<15% residue), reduced (15-30% residue) or conservational (>30% residue) (fig. 8), depending on the amount of operations and percentage of post planting crop residues on the surface. The move from conventional to conservation tillage practices offers greater advantage in preservation of soil attributes and water conservation. Conservational tillage costs are also lower due to reduction in machine hours and fuel costs (Rátonyi et al., 2018; Lamm et al., 2009). Notwithstanding

the advantages of conservational tillage, conventional tillage is still dominant in Europe (Jaskulska & Jaskulski, 2020).

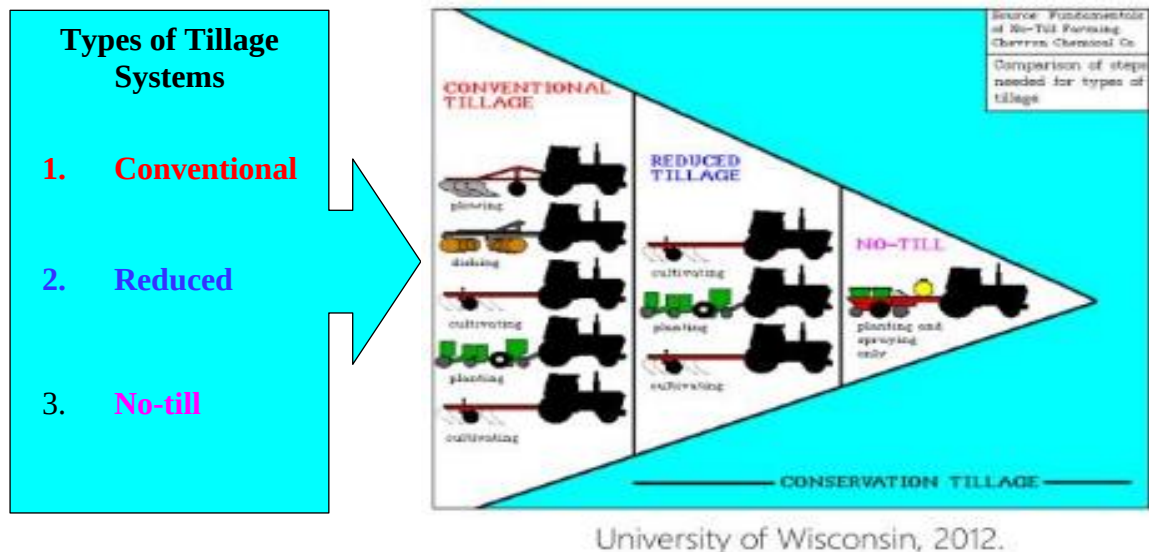


Figure 8. Types of tillage systems

Source: <http://com.agronomy.wisc.edu/Management/L007.aspx>

2.4.2.1 Conventional tillage

Conventional tillage entails disturbing the entire soil surface. Hence, the post-planting crop residue is significantly lower than conservational tillage and does not exceed 15%. The primary tillage tool is usually the moldboard plow. The completion of the primary tillage is carried out with simple implements, such as, smoother, roller or disc, while a cultivator is normally utilized for seedbed preparation. The procedure improving cultivation quality such as stubble stripping treatment, surface finishing is frequently omitted, while the number of operations in this tillage practice is the highest (5-9).

Conventional tillage can improve soil physical conditions, serve as a method for weed control and may also reduce incidence of pests and diseases. This tillage practice also facilitates the incorporation of crop residues, fertilizers and chemicals, and accelerates the soil warming process (Nagy, 2006). The disadvantages of this tillage system however, include high costs, increase soil temperature, loss of moisture, soil erosion and accelerated decay of organic matter, which in turn results in a decline in C and N contents of soil (Muñoz-Romero et al., 2015; Orfanou et al., 2019; Aziz et al., 2013; Shinoto, 2019). In studies conducted on cool humid soils in Canada, Angers et al. (1997), also found that the profile distribution of C and N in the soil varied with tillage systems and

in the 0–10 cm range, the C and N contents were higher in non-till compared to moldboard tillage, whereas, at deeper range of the soil profile (20–40 cm) the trend was observed to be reversed. As a result of the high costs and environmental concerns of conventional tillage, alternative systems, such as, no-till and reduced tillage are being explored (Drury et al., 2004).

According to Siemens et al. (1992), reduced tillage pertains to any system which is not as intensive as traditional tillage system. That is, either the number of operations is reduced or a tillage implement requiring lower energy consumption per unit area replaces an implement in the conventional system. Reduced tillage can be considered as an intermediate between conventional and zero-till, such as strip (ST) and ripper tillage (RT). These reduced tillage practices do not completely upturn the soil and therefore leaves a greater fraction of residues on the soil surface, compared to conventional tillage. Thus, moisture loss and potential for erosion is considerably reduced compared to conventional tillage systems (Bramdeo & Rátonyi, 2020b).

2.4.2.2 Reduced tillage

a. Strip tillage

In strip tillage the tilled width of the soil is usually 25-30 cm and the crop residues are removed from the tilled strip. The depth of strip tillage, ranges from 25 to 30 cm and soil disturbance affects 33% of the area. Hence, the forecrop residue remaining on the soil surface and can reach 60-80 %. Surface residue helps prevent soil from erosion (wind and water) and minimizes soil water loss. After stubble stripping and surface finish, the primary, secondary, fertilization and seedbed preparation are simultaneously executed in a single operation. Soil organic matter content is higher and moisture conservation is better, compared to conventional tillage. Fuel and labour costs are also lower due to elimination of some primary and secondary tillage. According to Nagy & Rátonyi (2013), strip tillage requires greater management, higher skill levels and more planning, compared to conventional tillage. The accurate implementation of strip tillage also requires aid of Auto Trac Guidance System.

Biological activities, soil moisture content and organic carbon content were all found to be higher in reduced tillage systems compared to conventional tillage, especially under

moisture deficit condition (Jaskulska & Jaskulski, 2020). According to Lamm et al. (2009), strip tillage provides a compromise between non-till and conventional tillage systems, by accomplishing most of the conservational benefits (water, soil) of non-till, while facilitating the handling of the increased crop residue and promoting early growth similar to conventional tillage.

b. Ripper Tillage

Ripper tillage is a type of reduced tillage system designed to limit compaction and control moisture. It is commonly used in areas which have problems with soil compaction. It is based on moderately deep loosening and is utilized in areas where the soil is extremely compacted in the 30-40 cm range of the profile. Primary tillage is carried out with ripper, coupled with total surface tillage with disc or plow. Surface finishing and seedbed preparation is usually in one operation or separately. It has the advantage of improvement and maintenance of the soil conditions, but it is not suitable for wet soil condition. The objective of using moderately deep loosening is to refine the condition of the deeper soil layer and to minimize the environmental damage (compaction) as a consequence of cultivation mistakes. The operation is carried out after stubble stripping and surface finishing.

Ripping becomes necessary if water permeability of the soil is below the average $<10 \text{ mm hr}^{-1}$, volumetric weight is greater than 1.50 g cm^{-3} , penetration resistance exceeds 3.5 MPa at field capacity, the water to air ratio is poorer than 80:20 and if there is a hard pan layer which affects water permeability and root growth (Nagy & Rátonyi, 2013). Schneider et al. (2017) posited that deep tillage was highly site-specific and soils with more than 70% silt is not suitable, due to increased risk (negative deep tillage effects). The successful use of ripper tillage also requires water content of the soil to be below the plastic limit throughout the tillage depth range (Borchert, 1975; Nagy & Rátonyi, 2013, Eck & Unger, 1985).

2.4.2.3 No-till

No-till systems also referred to as zero-till has the least number of operations which is 1-2 and disturbance of the soil surface does not exceed 10%. This system therefore has

the highest environmental benefits and is carried out mainly in dry areas and areas prone to drought, as well as in areas to be protected (Khan et al., 2017; Issaka et al., 2019).

Researchers in Kansas, USA have demonstrated that with prudent management and proper planning, maize can be successfully grown with conservation tillage systems. According to Rogers et al. (2007), uniform distribution of crop residues, proper planter adjustment and seed placement, soil testing, effective weed control and soil fertility management are all essential for successful production of corn in conservation tillage. In studies in Pakistan, Khan et al. (2017) found that conservation tillage also minimized leaching of nutrients, especially nitrates, compared with conventional tillage. Wang et al. (2015) reported similar findings which showed subsoil tillage (ripper) significantly enhanced absorption of soil moisture and reduce N leaching with higher spatial root density distribution, compared to conventional tillage.

The semi-arid type climate and increased occurrence of drought years in Hungary are accelerating the shift from conventional to conservational tillage system. According to Birkás et al. (2017), the main factors that fostered the adoption of conservation tillage practices in Hungary were drought condition and economic pressures. However, they noted that the significant progress made in soil conservation tillage in dry seasons is often eroded by return to conventional modes during wet seasons.

The selection of an appropriate tillage system ultimately depends on its profitability, which is based on the costs of the operations and the increase revenue generated from the improvement in grain quality and quantity. Tillage practices can also impact negatively on the environment and therefore, the choice and suitability of a tillage system, requires a holistic approach (Drury et al., 2004; Morris et al., 2010).

2.4.3 Effect of tillage systems soil properties and growth of maize

Tillage systems effect on physical properties of soil varied and sometimes contradictory. Hussein et al. (2019) reported highest infiltration rate in deep tillage (mean 245 mm hr⁻¹), followed by conventional tillage (129 mm hr⁻¹), and non-till (117 mm hr⁻¹), whereas, Khan et al. (2017) reported the highest infiltration rate in conventional tillage practices, followed by deep tillage treatment and minimum tillage plots. Findings by Blanco-Canqui et al. (2017) however, showed no significant difference in infiltration rate

between no-till, disk and chisel plow, although they observed the highest infiltration rate in conventional moldboard tillage. On the contrary, Fan et al. (2013) reported the lowest infiltration rate in conventional tillage (moldboard tillage), compared to no-till and attributed it to an increase in biological macro-pores which occur in no-till soil, than in moldboard tillage. The ambiguity in the results of tillage systems infiltration rate could be attributed to several factors, which include variation in agroecological conditions, soil type, structure, types of tillage implements, moisture content of the soil, etc.

Vyn & Raimbault (1992) found that the effect of tillage systems was influenced by soil types, as well as, the type of implements. They reported that the type of strip tillage implements influences soil tilth and crop growth and noted that the performance of Howard Rotaspikes and Rotavators closely matched moldboard tillage. They produced better tilth, taller plants, and yields were higher than Lely Roterra and strip-till cultivator. Nassir (2018) also found that the type of tillage implements (plow), and speed of the tractor had a significant influence on soil physical properties. He reported that bulk density, porosity and penetration resistance were substantially affected by type of moldboard plow, and bulk density was found to be lower (1.21 Mg m^{-3}) with higher tractor speed due to increase in pulverization of soil at higher speed.

Wang et al. (2015) found that chisel plowing lowers bulk density, increases total porosity and had higher nitrogen uptake compared to moldboard and other conventional tillage. Soil penetration resistance was generally found to be lower in conventional (MT) and deep tillage than reduced and no-till (Lin et al., 2016; Wang et al., 2015; Jabro et al., 2010; Hussein et al., 2019). Deep tillage offers the advantages of lowering soil bulk density, enhancing root penetration and facilitates the accumulations of N, P and K in aboveground plant parts (Cai et al., 2014).

Compared to conventional deep tillage, soil penetration resistance significantly increased under no-till in clay soil. The lower penetration resistance in deep tillage could be attributed to soil loosening and manipulation of the deeper soil layer (Jabro et al., 2010).

Lin et al. (2016) found that higher soil penetration resistance reduced root density distribution of maize both in the vertical and horizontal layers of the soil profile. They observed that with an increase in penetration resistance from 491 to 3,370 kPa, corn root

length decreased substantially and noted that the elongation of roots almost ceased when the soil penetration resistance exceeded 2,200 kPa.

2.4.4 Effect and interaction of tillage systems on yield of maize

Growth and yield parameters of maize were found to be significantly influenced by soil tillage systems (Kristo et al., 2013; Wasaya et al., 2017; Wang et al., 2015). Results of long-term experiments have shown that the effect size of soil tillage are modified mainly by the water supply of the prevailing crop-year, and during cropping seasons with dry spells, the benefits of subsoil tillage (deep) were higher than in moderate years (Nagy, 2007; Bramdeo & Rátonyi, 2020, Schneider et al., 2017).

In China, Cai et al. (2014), in a four-year study (2009-2012) found that tilling (subsoiling) to 50 cm depth, improved lodging resistance of maize, enhanced root development and increased grain quality and yield. They observed subsoiling to a depth of 30 cm increased maize grain and biomass yield by 12.8%, compared to 14.6% with a subsoiling depth of 50 cm.

Tillage practices have different effects on soil moisture preservation, which significantly affected maize yield (Simić et al., 2009; Rátonyi et al., 2018). Under drought conditions, soil tillage system significantly affected plant growth (height), the number and length of cobs, fertility of cob, kernels per cob and final grain yield (Kristo et al., 2013).

Vyn & Raimbault (1992) observed that strip tillage plant growth was delayed, and average yields were lower than moldboard tillage in silt loam and clay loam soils, by 10 and 12%, respectively. In Serbia, Simić et al. (2020) found maize yield in long-term experiment (2005–2016) was highest in conventional tillage (10.0 t ha⁻¹), compared to reduced and no-tillage, with 8.3 and 7.0 t ha⁻¹, respectively. They reported that in dry years however, the yield trend among the tillage systems was reversed, with higher yield recorded in reduced tillage than conventional tillage. In a 10-year average, Videnović et al. (2011) also found that maize yield was highest in conventional tillage treatments (CT) 10.61 t ha⁻¹, followed by reduced tillage (RT) and no-till(NT) with 8.99 t ha⁻¹ and 6.85 t ha⁻¹, respectively. Reduction in grain yield of maize in the order CT > RT > NT is also in agreement with findings of several researchers who reported lower yield of maize with

minimum tillage compared to conventional moldboard tillage (Kortorová et al., 2010; Habtegebrial et al., 2007; Doren et al., 1976; Uri, 2000).

While generally higher yields were obtained in conventional tillage, compared to reduced and no-till, several researchers have reported reverse trend under condition of low rainfall. In Ghana, Buah et al. (2017) reported mean grain yield of maize was 68% higher in non-till compared to conventional tillage and attribute it to better water conservation and weed control in non-till compared with conventional tillage. Roger et al. (2007) found that under consistently dry conditions, corn cultivated in strip tillage produced higher yields than those planted with conventional system, owing to improved moisture preservation. Similar report by Ferencsik & Rátonyi (2014), showed higher moisture retention in reduced tillage (strip and ripper tillage), compared to conventional tillage (moldboard). They observed that grain moisture content was also influenced by tillage systems and was significantly higher in subsoil tillage in drought year (2012), compared to moldboard tillage. However, Gwenzi et al. (2008), found tillage practices effect on grain moisture content and days to silking was not significant, but days to physiological maturity was significantly affected by tillage systems.

In a research conducted over a two-year (2008-2009) period in Pakistan, under semi-arid condition, Wasaya et al. (2017) found different tillage practices and N levels significantly influenced maize plant height, kernel yield, dry matter content and harvesting index. In both years of the experiment they found deep tillage with chisel plow, together with higher nitrogen application rate (200 kg ha^{-1}) significantly improved the dry matter content and maize grain yield compared to moldboard tillage.

Tillage and nitrogen interaction significantly influence soil carbon (C), nitrogen (N), nitrate and ultimately yield. Under zero-till and minimum tillage, the total C and N content of the soil was found to increase with nitrogen fertilization, whereas under deep tillage, the nitrate content increased with N-fertilization (Iqbal et al., 2013). In addition to its effect on nitrogen (N) availability for crop use, conservation tillage (reduced & non-till) can also influence the potential for nitrate (NO_3^-) leaching into groundwater and drainage system (Burgess et al., 1999).

Compared to conventional tillage, minimum tillage was found to reduce nutrient concentration in plants, especially N, which is most likely caused by an increase in N

immobilization and can be overcome with application of higher N rates (Malhi et al., 2001). Both the impact of tillage depth and the number of interventions is reduced or compensated for by improvement soil fertility and the impact of fertilization on yield and yield stability was significantly greater than that of tillage treatments (Györfy, 1976). Similarly, Schneider et al. (2017), also found that topsoil fertilization offsets extremely positive and negative effects of deep tillage.

Buah et al. (2017) observed no significant interaction between tillage practices and fertilizer treatments and concluded that maize response to fertilizer treatments was not affected by tillage systems. According to Mermon et al. (2012), apart from suitable selection of tillage operations, higher yields can be achieved through the maintenance of soil fertility with proper dosage and application method, coupled with the use of both organic and inorganic fertilizers.

Yu et al. (2019) found no significant interaction between tillage systems and N fertilization on yield-related traits of maize. They observed subsoil tillage treatments recorded higher leaf SPAD value during the R1, R2, and R3 growth stages. According to Grassini et al. (2011), apart from sowing and planting technology, soil cultivation and crop rotation (forecrop) have significant impact on maize yield. Al-Kaisi & Kwaw-Mensah (2018), found that tillage practices and crop rotation had significant effect (long-term) on soil health and productivity, through their influence on the physical, biological and chemical properties of the soil. They reported interactions between tillage practices and crop rotation in corn-soybean rotation (C-S) and continuous corn (C-C) was found to be significant. In the C-S rotation, they found corn yield in ST was not significantly different from moldboard plowing (MT) and deep ripping (RT) under C-S rotation.

According to Feng et al. (2018), deep tillage enhanced maize yield due to improvement in soil conditions and roots elongation and distribution. Rashidi & Keshavarzpour (2007) found that tillage practices had significant effect on plant population density, kernel per cob and hence, grain yield of maize.

Kristo et al. (2013) observed a significantly higher number of plants per area unit developed by the conventional plowing and by the ripping system, compared to the strip tillage. They found moldboard produced significantly longer and bigger number of corn-cob per area unit compared to ripping or strip tillage and fertilization was poorest in ripping tillage, whereas, fertility was far superior on plants from plow and strip tillage.

Yu et al. (2019) reported that subsoil tillage significantly improved LAI of corn varieties, in comparison to rotary tillage. They also found that subsoil tillage significantly reduced the sensitivity of corn roots to stress triggered by high planting densities by lowering reduction in length, dry weight and surface area of root. They found subsoil tillage allows for an increase in planting density of 15,000 plants ha⁻¹ and increased yield by 1.08-1.94 t ha⁻¹. Feng et al. (2018) posited that the positive effect of subsoiling on corn yield could be attributed to improvement in soil conditions and roots distribution. They found soil compaction was significantly reduced with subsoiling and soil moisture content and N availability was also improved.

In experiments conducted in two different locations to compare the effect of shallow spring and winter plowing on maize yield, Sulyok (2005) found that yields of maize were substantially lower in shallow spring tillage in all the crop-years (2001-2004) and concluded that winter plowing was superior to shallow spring tillage.

In studies conducted on three tillage systems (rotatory tillage -RT, non-till-NT and subsoil tillage-ST), Wang et al. (2015) found the number of ears per hectare among the three tillage systems did not varied significantly. However, they noted that the kernel number, kernel weight and grain yield and N uptake were highest with subsoil tillage. Memon et al. (2012) observed that tillage practices and fertilization had significant influence on the number of cobs plant⁻¹, the number of kernels cob⁻¹ and 1000-kernel weight. They reported that the number of cobs per plant in deep tillage exceeded that of conventional tillage, while non-till treatment had the lowest number of cobs per plant and hence, the least 1000-kernel weight. They observed deep tillage had taller plants and attribute the higher yields to the greater loosening effect of the soil profile, compared to conventional and zero tillage.

Although some researchers have observed significant differences in maize yield among tillage treatments, others have not. In Japan for instance, Shinoto et al. (2020), compared yield of maize hybrids in rotary tillage and chisel plow tillage and found maize growth was generally unaffected by tillage system. They observed that even though differences in the early growth stages were significant, in latter stages the differences were not significant and grain yield was also not significantly different. Similarly, Orfanou et al. (2019), reported that although higher yields were recorded in conventional tillage over conservation tillage plots, the yield differences were insignificant, and concluded that

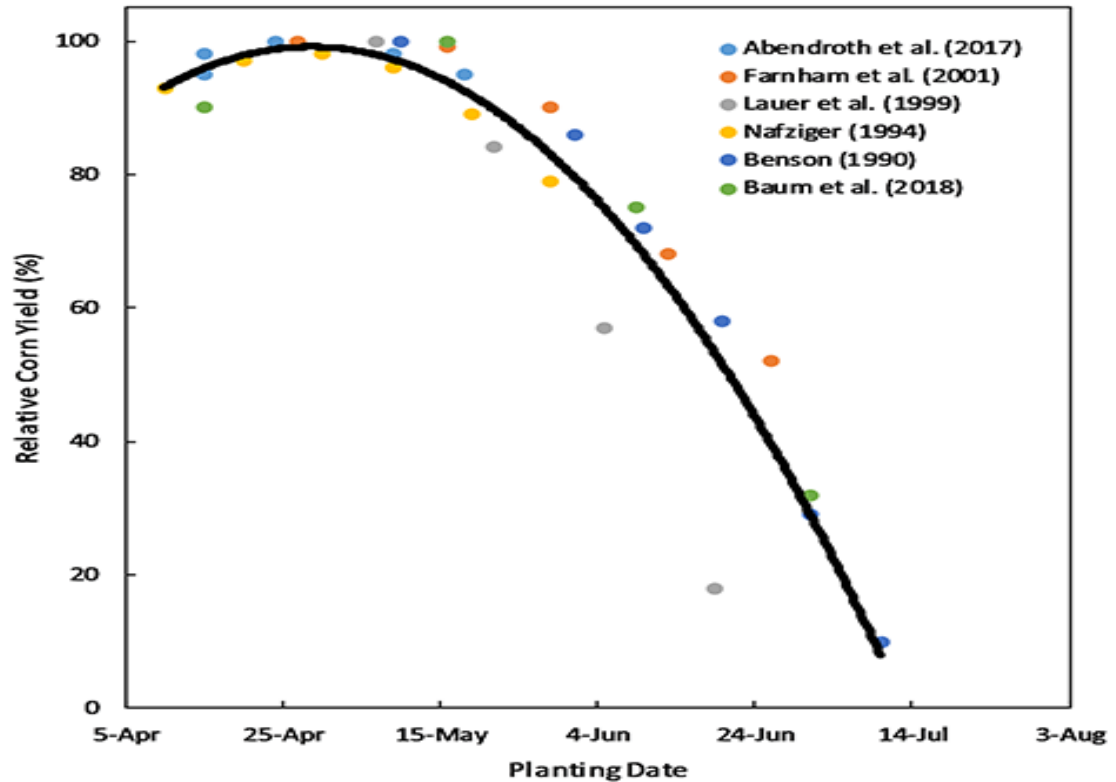
conservation tillage could be an alternative for moisture preservation, while simultaneously achieving decent yield. In Bangladesh also, Rahman et al. (2015) found that tillage had no significant effect on maize yields and concluded that maize yields are independent of tillage practices and are more dependent on irrigation practices.

Several researchers have found that on well-structured soil, tillage practices do not significantly influence the yield and mean yield can be improved if soil fertility is maintained with adequate fertilizer dosage (Kismanyoky & Balazs, 1996; Nagy, 1996; Fenyves, 1997).

2.5 SOWING TECHNOLOGY

Decisions on the sowing date and hybrid relative maturity determines the yield potential of maize in every environment (Baum et al., 2019). The optimum sowing technology essentially impacts on the efficiency levels of other agronomic factors and thus, the yield (Pepó & Csajbók, 2013). The selection of corn sowing date requires special attention, as sowing is carried out when the soil temperature is 10°C. Under normal weather conditions, this corresponds to the period between 20th April and 5th May. According to Ross et al. (1996), maize responds primarily to temperature and its growth and development is not dictated by day length. As a result, the sowing date of corn is more dependent on soil and air temperatures, rather than calendar date. They found early planting was more advantageous, with fewer irrigations, reduced pest damage, earlier harvest and typically higher yields, than late planting. Similar reports by Nagy (2006) and Tótin & Pepó (2018), showed early planting reduces risks associated with July drought and grain moisture content was also lower. Berzsenyi & Dang (2006) found that although earlier sowing (14th April) resulted in significantly higher yield than sowing at a later date, the yield stability was much lower for early sowing. Similarly, Maresma et al. (2019), found that early sowing date increased the days from planting to emergence, while late sowing date resulted in a reduction in the days to maturity, and had superior forage yields, higher grain humidity, and much taller plants.

Several studies have confirmed yield loss can be significant when sowing is extended beyond the recommended opportunity window, as shown in fig. 9 which presents a summary of six experiments conducted in the central Corn Belt, USA, from 1994 to



Source: <https://cropwatch.unl.edu/2019/corn-planting-windows-across-corn-belt>

Figure 9. Effect of sowing date on relative corn yield

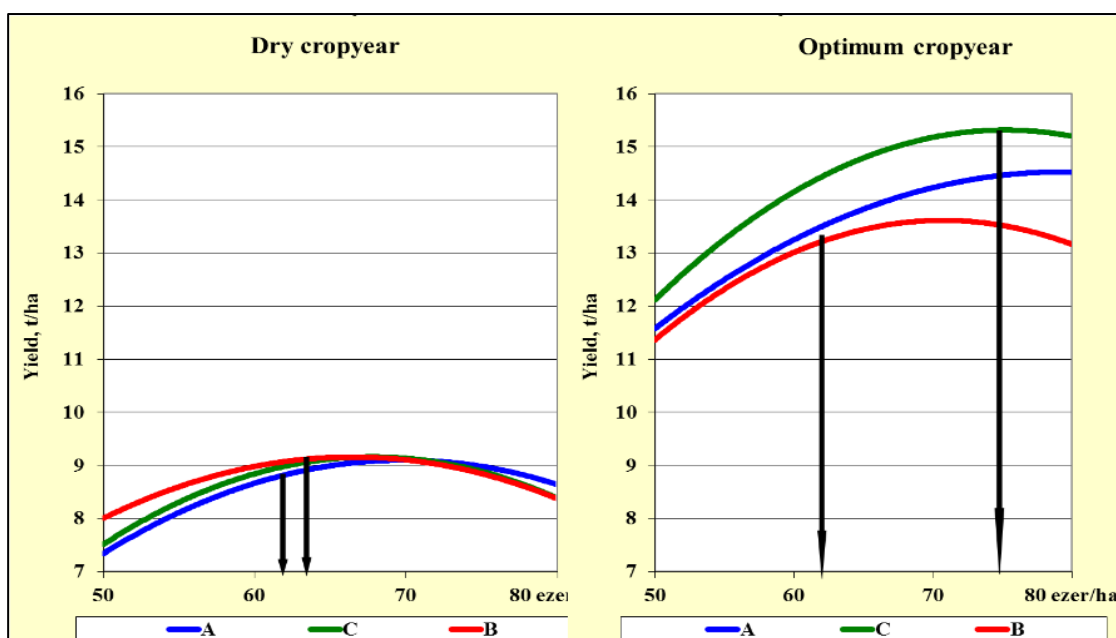
2018, (Baum et al., 2019). The early sowing of a full-season hybrid, however, is not an assurance for high grain yield since other factors such extreme weather and nutrient stresses can affect yield during the season (Edmeades et al., 2000).

2.5.1 Plant density

Accompanying the significant improvement in maize yield since the introduction of hybrid maize, plant population density has also substantially increased. Increasing the planting density for a given hybrid, increases yield up to a maximum, beyond which yield declines (Tollenaar et al., 1994; Sárvári, 2005). Establishing the optimum plant density for a given genotype is paramount in sustainable maize production and is determined based on several factors, which include the genetic traits, hybrid response to density, duration to maturation, sturdiness of the stem, soil features, initial spring

water supply, crop-year effect, soil fertility, irrigation and level of agrotechnological inputs (Pepó, 2012; Vad et al., 2007).

Murányi (2015) found that hybrids responded differently to changes in population density and row spacing and their performance was modified by the crop-year (fig.10).



Source: Pepó, P, Csajbók J. (2013): Integrated crop production 1

Figure10. Plant density x crop-year x genotype(A, C, B) interaction on yield

According to Sachan & Gangawar (1996), maize planted at row spacing of 60 cm had significantly taller plants and higher number of functional leaves and larger stem diameter, compared to those planted at narrower row spacing of 45 cm.

Increasing plant density, increases leaf area index and growth rate of the crop and consequently, the crop water consumption (Tetio-Kagho & Gardner, 1988; Baghdadi et al., 2012).

Plant density has significant influence on growth (stem diameter, plant height) and yield parameters (grain ear⁻¹, number of kernel ear row⁻¹, harvest index, cobs plant⁻¹, length of cob, diameter of ear) of maize (Sharifi et al., 2009; Abuzar et al., 2011; Xue et al., 2002).

Maize grain yield decreased when the planting density exceeded the optimum number of plants, primarily because of a decline in the harvesting index and increase in stem lodging (Tokatlidis & Koutrubas, 2004).

Murányi (2015) reported that at row spacing of 76 cm, yield increased ranged from 0.84%-11.59 % with a mean of by 4.12%, but only 2.2% yield gain was realized when the plant population was increased from 70,000 to 90,000 plants ha⁻¹. Higher planting density resulted in higher yield and yield variations and impacted negatively on individual plant productivity. Several mid-south evaluations in the USA showed that 38-inch (96 cm) rows spacing resulted in 10 -15% yield reduction compared to 30-inch (76 cm) row spacing (Ross et al., 1996).

Bramdeo & Rátonyi (2020a) reported mean yield of 80,000 plants ha⁻¹ was 1.15 t ha⁻¹ higher than 60,000 plants ha⁻¹, concurrent with 15.6% decline in individual plant productivity at the higher density and the reduction in individual plant productivity varied with the genotypes. Similar results were reported by Testa et al. (2016), who conducted two experiments in NW Italy to evaluate the yield benefits of high plant density on two hybrids and found higher plant density led to a 20% decrease in the stalk area, 5.2% decrease in leaf greenness and a reduction of cob length of 10.8%. It also negatively affected the kernel weight (-7.1%) and increase overall yield, while there was a reduction in grain yield per individual plant due to competition.

Higher yields with increasing planting density can be attributed to the larger interception of solar energy (Hoeft et al., 2000). In research conducted in China, to determine the effects of canopy light intensity on stalk strength and lodging resistance in densely populated maize, Xue et al. (2016), found that in densely planted maize that light intensity had significant influence on the accumulation of dry matter, sturdiness of the internode, and lodging rate. Their results demonstrated that grain yields significantly increased with a higher planting density and the lodging rate also increased significantly with higher plant density. They found lodging rate was highest (90%) at grain filling stage and lodging resistance and grain yield were highly influenced by the maize variety. Varieties with smaller, larger and medium-sized leaves distributed in upper, middle and lower canopy respectively, were most resistant to lodging and had higher yields.

In Hungary, the optimum plant density in dry years was found to be significantly lower than in years with optimum levels of rainfall (Pepó et al., 2008; Berzsenyi et al., 2011; Bramdeo & Rátonyi, 2020c). According to Sárvári & Pepó (2014), hybrids with wide optimum interval were found to be more adaptable to various agro-ecological conditions and posited that the uniqueness of each hybrid demand that hybrid-specific technology

be employed for optimum results. The optimum planting density in Hungary ranges from 68-82 thousand plants ha⁻¹ depending on the hybrid.

The optimum plant population density, which produced the highest yield has increased over the years due to better plant density-tolerance of the newer maize genotypes, but the potential yield per plant remains unchanged (Tokatlidis & Koutroubas, 2004). According to Sárvári (2005), plant density has a determining effect on overall yield, as well as the individual plant productivity. By increasing the plant population density, the yield per unit area increases but the yield per plant decreases with an increase in population density.

Pepó & Murányi (2014) found that the ideal plant densities in Eastern Hungary were 70,000 and 90,000 plants ha⁻¹ for specific hybrids. Their results demonstrated marginal yield increase (412-1,111 kg ha⁻¹) with an increase in planting density from 70,000 to 90,000 plants ha⁻¹ and posited that the higher population density could significantly increase yield loss under unfavorable environmental and agrotechnological conditions. In India, Singh & Tajbaksh (1986), found that dry matter accumulation in maize varied with planting density and was significantly higher at 100,000 plants ha⁻¹ (60 cm x 16.6 cm), compared to those with 50,000 plants ha⁻¹ (60 cm x 33.3 cm) and 75,000 plants ha⁻¹ (60 cm x 22.2 cm). Similar findings were also reported by Singh et al. (1997).

According to Pepó & Vad (2008), the optimum plant density of maize in dry crop-year was found to be 50,000 plant ha⁻¹, while in favorable crop-year (wet) it was 80,000 plant ha⁻¹. Similar findings were reported by Berzsenyi et al. (2011); Sárvári (1995); and Bramdeo & Rátonyi (2020), who found in drought years, optimum yield for maize was achieved at lower planting density. Kansas State University Researchers have also found that maize can compensate by producing larger ears if the populations are too low to utilize the growing conditions (Rogers et al., 2007).

In Vietnam, Tuong et al. (2019) reported that the highest yield (7.35 t ha⁻¹) was obtained with 66 thousand plants ha⁻¹ and N180 kg ha⁻¹. They found corn yield and yield components were significantly affected by the planting densities and fertilizer rates. Cob length and diameter, grain rows per cob, and 1000-grain weight varied considerably with changes in fertilizer rates and planting densities.

Yan et al. (2016), found maximum grain yield and nitrogen use efficiency (NUE) were achieved at 75,000 plants ha⁻¹ and both lower (60,000 plants ha⁻¹) and higher densities (90,000 plants ha⁻¹) resulted in reduction in yield and NUE. They observed that 75,000 plants ha⁻¹ had greater accumulation of biomass during the grain-filling stage and biomass allocated to kernels was also higher compared to the lower (60,000 plants ha⁻¹) and higher densities (90,000 plants ha⁻¹).

In Ethiopia, Zeleke et al. (2018), reported significant differences ($P < 0.05$) among planting densities. They observed that maize plant height, the leaf area index and height of ear increased significantly with an increasing in planting density (from 44,444 to 88,888 plants ha⁻¹), while the length and diameter of the cobs and kernels per cob decreased at the higher density. They found that grain yield increased by 65.16% at the higher density (88,888 plants ha⁻¹) with N 161 kg ha⁻¹, compared to the lower density (44,444 plants ha⁻¹) with a N 92 kg ha⁻¹. Similarly, Xu et al. (2017) found that planting density, N fertilization and their interaction had significant influence on grain yields and yield components. They reported that grain yield increased by 7% when planting density was increased from 67,500 to 90,000 plants ha⁻¹ and observed no significant difference in yield between N180 and N360 treatments. They found with increase in planting density the average ear number increased, whereas, kernel number and thousand kernel weight displayed significant decreases and posited that maize productivity can be maximized with use of high density-tolerant genotypes and efficient Nitrogen utilization.

In addition to its influence on yield, a positive but non-significant correlation was found to exist between planting density and starch content of maize grains (Virág et al., 2020). Lihang & Lumingkewas (2017), reported maize planting distance significantly affects the starch and sugar content of the grains and maize planted at a wide planting distance was found to produce higher starch and sugar content. However, Bernhard & Below (2020), found that changes in plant population density had no significant influence on grain quality and compositional concentrations of starch and protein.

2.6 CROP ROTATION

It has been well established that the yield of monoculture maize was always lower than maize inserted into a system of rotation. In many regions of the world, maize is cultivated either as a partial or total monoculture crop. The most common practice is the insertion of wheat for two years, after 2-3 years of monoculture cropping (Nagy, 2006). Yield potential of maize can be realized in biculture cropping system; however, crop rotation needs at least 3-4 years of planning for proper implementation and execution. Good preceding crops for maize in Hungary include winter wheat, winter barley, spring barley, triticale, potato, industrial plants (e.g. rape) and leguminous plants, such as soybean. According to Pepó & Csajbók (2013), in biculture cropping system, consideration must be given to the time of removal of the current crop, when the subsequent crop is being selected. After early ripening (FAO 200-300) hybrids, winter spikéd cereals can be cultivated and after late harvest of maize, spring sowing crops such as pea, soybean, sunflower can follow.

The positive impact of crop rotation resulted from its effects on soil nutrient status, pest cycle and water availability (Ahmed, 2015). Crop rotation is considered the most economical and safest way of controlling weeds, diseases and pests. Seed production of due quality cannot be performed in region where monoculture prevails (Nagy, 2006). Maize yield was generally found to be lower in monoculture compared to bi or tri-culture with wider yield differential in the dry seasons (Pepó, 2001). Yield decline in dry years after 10-15 years of monoculture ranged from 1-3 t ha⁻¹ compared to biculture maize (Sárvári, 1995).

Sound crop rotation enhanced the soil nutrient status and can reduce fertilizer requirements. Crop rotation enhanced yield productivity through the improvement of soil physical, chemical, and biological conditions (Jawson et al., 1993; Boyer et al., 2015). It also improves nitrogen use efficiency (NUE) by reducing requirements for external inputs of N fertilizer (Huggins & Pan, 2003; Pikul et al., 2005). Nitrogen fertilizer requirement for optimum yield was found to be lowest in tri-culture (113 kg N ha⁻¹), compared to bi-culture (147 kg N ha⁻¹) and monoculture (187 kg N ha⁻¹) (Pepó, 2001). In addition to improving yield, crop rotation also influences the nutritional quality of maize grains, due to the differences in soil nutritional status between monoculture and biculture cropping systems. Loss of kernel quality was reported with diminishing Zn

content ($4\text{--}5\text{ mg kg}^{-1}$) in monoculture maize (Nagy, 2006). Grain protein content was also found to be higher under biculture cropping system, compared to continuous maize (Mahama, 2018; Negash et al., 2018).

Huzsvai & Széles (2009) observed the residual water content of the soil was always higher after winter wheat forecrop, compared to monoculture cropping system with maize as the preceding crop. They also reported that more easily accessible nitrogen was found in the soil under winter wheat forecrop, as a result of which, yield decline was smaller in cases where the water supply grossly exceeded the demand of the crop.

In corn-soybean rotation, yield of both maize and soybean increased by 21% and 9% respectively, compared with monoculture (Wilhelm & Wortmann, 2004). Similarly, Lauer (2010), reported greater yield advantage in both maize and soybean when they are grown in rotation compared to monoculture. Nagy (2006) posited that yield decline experience in monoculture maize resulted mainly from exhaustion of the soil water supply and maize monoculture should therefore be interrupted after 10-15 years, especially in areas where precipitation is below optimum.

Pepó & Sárvári (2013) found that the optimum nitrogen dosages on chernozem soil in sustainable maize production are as follows: $\text{N}60\text{--}120\text{ kg ha}^{-1}$ for triculture crop rotation, while $\text{N}100\text{--}140\text{ kg ha}^{-1}$ and $\text{N}140\text{--}180\text{ kg ha}^{-1}$ for bi and monoculture, respectively. Sárvári (1995), reported a reduction in fertilizer application rates in bi and triculture crop rotation systems. Nitrogen fertilizer dosage applied after winter wheat in biculture was 40 kg ha^{-1} less ($60\text{--}80\text{ kg ha}^{-1}$) compared to monoculture ($100\text{--}120\text{ kg N ha}^{-1}$), while in triculture the applied dosage is even lower ($50\text{--}60\text{ kg ha}^{-1}$).

The highest yield increasement as a result of crop rotation is commonly observed in the control plots (N_0). Wilhelm & Wortmann (2004) reported higher grain yield for corn and soybean in rotation, ($7.10\text{ vs. }5.83\text{ t ha}^{-1}$) compared to continuous cropping for both corn and soybean ($2.57\text{ vs. }2.35\text{ t ha}^{-1}$). According to Below (2018), soybeans forecrop can increase corn yield by 25-bushel (635 kg) and if corn was the previous crop, there will be a 25-bushel (635 kg) penalty, just the opposite. He attributed the cause of monoculture yield penalty to crop residue which acts like a sponge and prevents small rains from infiltrating the soil and also immobilizes key nutrients, particularly nitrogen and sulfur. Below (2018), also stated that if you have a dry July, the residue will release allelochemicals that interfere with the growth of the corn crop.

Maize can be incorporated as part of a crop rotation system especially with preceding crops that increase the humus and nitrogen content of the soil. In many parts of the world, maize is grown as a monoculture crop or rotated with wheat or soybean. In Hungary, maize is traditionally grown after wheat (Nagy, 2006). Crop rotation is the most economical and environmentally friendly way of controlling weeds, diseases and pests.

The effect of weather conditions and irrigation on maize yield is significantly influenced by crop rotation and was found to be more pronounced under monoculture cropping system with lower yield than in biculture and triculture maize (Pepó et al., 2008). Crop rotation improves soil nutrient, helps to mitigate yield fluctuation and allows for a reduction in applied fertiliser rates. The benefits of crop rotation arise from enhancement of soil nitrogen, availability of phosphorus, exchangeable magnesium and efficient cation exchange capacity (Uzoh et al., 2019). Seymour et al. (2012) reported that the rotational benefits realized from the forecrop depends on various factors, such as the crop type, its residue production and the soil condition. Crop rotation helps to improve soil life through improvements of soil bacterial activities, as it was found that the soil bacterial content was significantly lower in monoculture cropping system. In a system of crop rotation, after winter wheat, 59 million bacteria per gram of soil were recorded, compared to 16 million in monoculture maize (Nagy, 2006). Suitable forecrop is also the most effective way of controlling the larva of the American maize bug, as well as improving soil water storage and nutrient such as Zinc which are essential for optimum yield (Brankatschk & Finkbeiner, 2017).

Dias et al. (2015), found that the forecrop in a rotation system affects the microbiota community inhabiting the plant rhizosphere in the soil and influences the growth and development of maize seedling. The influence of crop rotation on the microbial communities could be beneficial to plant species through enrichment of microbial taxa that have positive influence on crop growth (Benitez et al., 2017; Dias et al., 2015). The pest, *Diabrotica v. virgifera* can significantly reduce yield of maize, and crop rotation has been an effective and widely used method of control (Márk et al., 2014). Benefit of corn-soybean rotation was also observed to be greater in no-till than with tillage (Griffith et al., 1988; Lund et al., 1993).

Roth (1996), reported that maize cultivated in rotation with soybeans forecrop, can save on soil insecticide and atleast 40 lbs ac⁻¹ nitrogen fertilizer. According to Pepó et al.

(2008) crop rotation significantly influences the effect size of weather and irrigation on the yield of maize. The interaction between water and nutrient supply was evident in mono, bi, triculture rotation system and was more pronounced in monoculture cropping system with the lowest yield, compared to bi and triculture maize.

Crop rotation can support the successful implementation of conservation tillage practices, reduce production costs with fewer inputs and lower fertilizer dosages (Bramdeo & Rátonyi, 2020; Roth, 1996; Sárvári, 2005). Birkás et al. (1999) found weed infestation was successfully overcome by applying a maize - winter wheat crop rotation in Hungary.

In North China Plain, Wang et al. (2020a), demonstrated that a diversified cropping system (DCR) can improve soil condition and enhanced system productivity compared to winter wheat–summer maize biculture (WM) system. They found that even though irrigation and fertilization inputs of DCRs were less than the control, there was no significant reduction in wheat yield in comparison to the control (7.79 Mg ha^{-1}) and concluded that DCRs offers greater benefits, especially, peanuts→WM and potato→WM rotations over WM double-cropping. Similar report by Sárvári (1995), showed applied fertilizer dosage in triculture rotation was lower ($50\text{-}60 \text{ kg ha}^{-1}$) compared to biculture.

2.7 NUTRIENT SUPPLY

The nutrient demand of maize is pronouncedly high, with nitrogen (N) being in the highest demand among the macronutrients, followed by potassium (K) and phosphorous (P). Maize utilizes 25 kg N, 13 kg P and 22 kg K_2O to produce one ton of biomass (Nagy, 2006). Maize absorbs nutrients both from the soil reserve and from applied fertilizers. Even though livestock manure is preferential for maize, it is not commonly applied due to inadequacy of supplies (Pepó & Csajbók, 2013). The applied fertilizer dosage for maize depends on various factors which include the nutrient status of soil, anticipated yield level, specific nutrient demand and characteristics of the hybrid, water supply of the soil at planting and the type of preceding crop (Pepó et al., 2008). Fertilization was also observed to improve water use efficiency in maize (Széles et al., 2018; Csajbók et

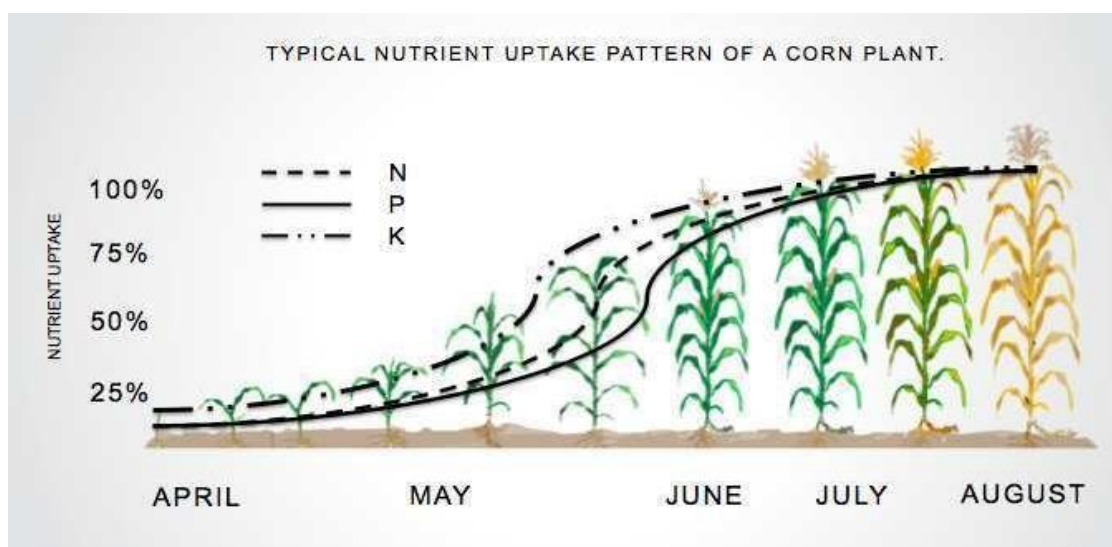
al., 2014). It is one of the most important agrotechnological inputs due to its significant influence on crop development and ultimately yield.

Fertilization account on an average for approximately 35% of yield variance (Pepó & Karancsi, 2014; Berzsenyi & Györfy, 1997; Bramdeo & Rátónyi, 2020). It also represents a huge cost and applying more than the crop can utilize reduced economic efficiencies and can result in environmental pollution. According to Debreczeni (1980), the applied fertilizer dosage should be established based on profitability, rather than highest yield.

Maize requires an ample quantity of nitrogen for the establishment of its large vegetative and generative mass. Nitrogen is an essential and major yield determining factor in maize production system. It accounts for 1 to 4% of dry matter of the plants and when it is deficient, photochemical processes of plants are adversely affected and growth is reduced (Haque et al., 2001; Adediran & Banjoko, 1995; Shanti et al., 1997; Kalaji et al., 2014). Nitrogen is an essential component of amino acids and chlorophyll and several other compounds necessary for plant growth and development. It also mediates the uptake and utilization of other plant nutrients, including potassium and phosphorus (Brady, 1984).

Potassium uptake in maize is relatively high and it has a variety of functions in the crop development and yield formation processes, and its deficiency can drastically affect growth and yield of maize. Phosphorus is also an important macronutrient required for root and grain development in maize. Phosphorus deficiency results in metabolic disorder and delays flowering and ripening is delayed (Grant et al., 2001).

The determination of fertilizer dosage of corn, requires knowledge of the plant particular nutrient demand, based the percentage of the nutrients per 100 kg main and by-product (N=2.5 kg ; P_2O_5 =1.1 kg; K_2O = 2.2 kg ; CaO =0.8 kg ; MgO=0.3 kg). The average fertilizer dosages in maize in Hungary are as follows: N=60-160 kg ha⁻¹; P=60-80 kg ha⁻¹ and K= 100-150 kg ha⁻¹ (Pepó & Csajbók, 2013). The adequate supply of nitrogen during the cropping period is paramount for the realization of prime growth and development. The rates of absorption of the macro nutrients (N, P, K) are different and depends on the plant growth stage (fig. 11).



Source: <https://inthefurrow.com/2017/12/19/plant-soil-nutrient->

Figure 11. Maize nutrient uptake (NPK) during the vegetative period

Uptake of potassium in maize is highest during the vegetative phase, while nitrogen uptake peaks during the flowering-fertilization phase. Phosphorous absorption is balanced along the growing season (Pepó & Csajbók, 2013).

Maize NPK uptake and assimilation is influenced by the applied fertilizer dosage, genotype and crop-year, particularly as it relates to precipitation amount and distribution during the growing season (Pepó & Karancsi, 2017; Széles et al., 2018).

According to Pepó & Karancsi (2017), increasing fertilizer dosage N90 to N150 kg ha⁻¹ significantly reduced the nitrogen use efficiency. Similar observations were made by Zhang et al. (2015), Bramdeo & Rátonyi (2020) and Széles et al. (2018).

Fertilizer application in maize production system in Hungary is carried out in different stages. Initially, the basic dressing which include the full dosages of phosphorous, potassium and 0-30% of the nitrogen are applied to the soil in the autumn and the remaining 70-100% of N is applied and incorporated into the soil during seedbed preparation in the spring. Starter fertilization is then applied together with the sowing of maize and consists of small portion (15-30 kg ha⁻¹) of fertilizers with macro- (mainly P), meso- and micro elements. During the vegetative phase, N-fertilization (10-25% of N) is applied by interrow cultivator, while application of microelements (mainly Zn) and leaf manuring is carried out at the V₆-V₁₂ growth stage. Zinc (Zn) role is of significant

importance, and its deficiency has adverse effect on growth and development (Pepó & Csajbók, 2013).

Manganese (Mn) is also an essential micronutrient and its deficiency is often observed in soils which are inadequately drained and have high humus content. At high pH manganese availability to the plant may also be restricted. Gong et al. (2010) found Mn deficiency in maize lead to decreases in the photosynthetic capability of the leaf through a reduction in the content of chlorophyll a. They concluded that manganese deficiency is detrimental for efficient light energy conversion in chloroplasts, as a result of which maize growth is inhibited.

In field experiments in Pakistan, Amanullah et al. (2016), found that applying foliar potassium and zinc at the rate of 1–3% and 0.1–0.2% respectively, was more advantageous for growth and yield parameters of maize during moisture water deficit conditions. Application in the vegetative stage improved growth and resulted in an increase in yield than spraying at the reproductive stage. The results also revealed that higher dosage of applied K, up to 90 kg ha⁻¹ in two equally divided parts i.e. 50% at sowing and the remaining 50% at V₆ stage, enhanced growth and productivity of maize under semiarid conditions.

2.7.1 Effect of fertilization on grain yield and nutritional composition

In China, Xu et al. (2017) in a two-year study observed that lowering the applied N dosage from 360 to 180 kg ha⁻¹ had no significant effect on grain yield of maize and there was a 6.2% improvement in Nitrogen use efficiency. In addition, they reported greenhouse gas emission decreased 46.2%. Similarly, Berzsenyi & Dang (2006), found that the yield amount and stability were not significantly different for N160, compared to N 240 kg ha⁻¹, while 80 kg N ha⁻¹ rate showed similar stability but with lower yield (≈ 1.3 t ha⁻¹).

Lana et al. (2014) found increasing nitrogen rates, increased the N content of the leaf, stem circumference, height and length of the ear, the total rows and grains per ear, kernel weight per ear, 1000 kernel weight and overall yield. Similarly, Inamullah et al. (2011), found that higher nitrogen levels of up to 240 kg ha⁻¹ significantly improved the number of ears plant⁻¹, the ear length, kernels ear⁻¹, 1000-kernel weight, grain and biological

yields, as well as the harvesting index. The significant increase in harvesting index and crop yields, as a result of higher fertilizer dosage could be ascribed to enhancement in cell division and enlargement (Shivay & Singh, 2000).

According to Bocz & Nagy (1981) optimum supply of nitrogen significantly increases the number of grains per cob, and to a limited extent, increase of thousand kernel weight. In research conducted in Serbia, Šarčević-Todosijević et al. (2018), found higher rates of nitrogen up to 120 kg ha⁻¹, increased plant height, total leaves, cob length, total grain rows and grains per cob, after which all measured parameters declined with further increase in N fertilization (N180 kg). They concluded that the optimum fertilizer rate for maize on Chernozem was, N 120 + P 90 + K 60 kg ha⁻¹. Nagy (2003) found that the yield increases from irrigation was greater at higher fertilizer dosages and attributed the increase to the positive relationship between the two agronomic factors. In similar research, Simkó et al. (2020) found that maize ear and 1000-kernel weights were affected by the applied dosage of N and water supply, but the kernel per cob ratio was dependent mainly on the genetic makeup. They concluded that N80 kg ha⁻¹ was the optimal dose for maize under dry conditions, while under favorable weather conditions, 160 kg ha⁻¹ was optimal. Similarly, Kovács (2018), after comparing the hybrids' performance with N160+PK fertilizer and N80 + PK concluded that the N80+PK was most ideal. Bramdeo & Rátonyi (2020) also found N160 yield increasement was greater in favourable crop-year (2016), compared to unfavourable year (2015). Several researchers have observed that the effect size of fertilization and irrigation varied significantly with crop-years and under favourable conditions with adequate water supply, fertilisation significantly improved yield, while in excessively dry years, its yield increasing effect diminished (Pepó, 2007; Sulyok, 2005; Meges, 2005; Nagy, 2007; Berzsenyi, 2010).

Széles et al. (2018a) reported that under favourable weather conditions, optimum yield was obtained with lower fertilizer dose of 120:92:108 kg NPK ha⁻¹, while under unfavourable growing conditions higher treatment dose of 180:184:216 kg NPK ha⁻¹ was required. They posited that yield variation during the examined period cannot be explained merely by nutrient supply and temperature of the cropping season, but the sensitivity of maize response to the quantity of precipitation during the cropping season.

Nitrogen use efficiency was found to vary among genotypes and yield response was also different, depending on the growth stages at which top dressing N was applied. Széles

et al. (2019a), reported that the most favorable income level of N was 150 kg ha⁻¹ with basal dressing of 120 kg N ha⁻¹ and +30 kg N ha⁻¹ (V6₁₅₀) top dressing, applied at the early V6 phenophase. They found Renfor hybrid (FAO 320), yield profitability peaked with V6₁₅₀ treatment, independently of the prevailing environmental factors, whereas Armagnac (FAO 490) hybrid, the top dressing at the V12 phenophase provided the highest profitability.

High and sustainable plant yields can only be achieved through the combined usage of both inorganic fertilizers and manure (Raman et al., 1996, Singh et al., 1999). According to Kramer et al. (2002), the higher yields from combined usage of synthetic fertilizer and pen manure could be attributed to increase nutrient accessibility and reduction in losses through conversion of inorganic nitrogen into organic forms.

Among the macro nutrients required by the maize plant, Nitrogen is utilized in the largest quantity and has the highest impact on yield and profitability. Due to its highly soluble nature and easy transformation into nitrous oxide, N fertilizer presents the greatest risk to the environment (Tao et al., 2018). An important goal in modern intensive farming practises, is the improvement of nitrogen use efficiency (NUE) by supplying the needs of the crop, while eliminating the risk of polluting the environment (FAO 2020).

To aid better nutrient management strategies and improve fertilizer use efficiency, the 4Rs of Nutrient Stewardship is being encouraged which entails the Right fertilizer source, at the Right rate, at the Right time, and in the Right place (4R) (IPNI 2012). According to Below (2018), the future of corn plant nutrition is a “feed the plant approach” as opposed to a “feed the soil approach.”

In addition to improving yield, N application also has significant influence on the nutrient content of maize grain, particularly the protein contents. The higher the rate of applied N fertilisation, the higher is the protein content in maize grains (Rehman et al., 2020; Széles et al., 2018). According to Simić et al. (2020), lower rate of N fertilization and less intensive tillage improved the accumulation of starch and oil.

2.8 IRRIGATION AND EFFECT ON YIELD

Nagy (2006) opined that it is possible to execute profitable production with most cultivated crops without irrigation, however, the fluctuation of yields and the assurance of yield security and quality production requires irrigation.

Irrigation is integral to the production of maize, as yields are significantly lower in non-irrigated, compared to irrigated treatments (Orfanou et al., 2019). According to Lamm et al. (2009), severe suboptimal irrigation can affect all or some corn plants from reaching the optimum yield threshold. Huynh et al. (2019) found that under dry conditions in sandy soil, yield increased significantly with irrigation and was the most yield limiting factor, compared to crop rotation and tillage.

Water deficit and high temperature as a result of drought condition, limits crop yield and increases soil erosion. Under drought condition the physiological mechanisms of the plant for water conservation and maintenance of turgor pressure hinder photosynthesis and expansion of leaf area, while high temperature under adverse moisture deficit conditions can result in unnecessary respiration, advance phenological development and irreparable damage (Martinez & Basso, 2020).

In Hungary, only 2.1% of the agricultural area is irrigated. Irrigation becomes necessary when precipitation and water reserves of the soil are inadequate. Climatic conditions in Hungary tend to arid (Nagy, 2006) and irrigation is necessary, since only 25% of the seasons could supply the cultivated crop with adequate water. The majority of floral biomass is produced by precipitation management and supplemented by irrigation.

Irrigation increases yield, minimizes fluctuation and improves grain quality (Csaba et al., 2013). Maize water requirements range from 500-600 mm during its vegetation period and the most crucial periods for water supply include tasseling, silking and early grain formation (Pepó & Sárvári, 2013). Results of long-term experiment have demonstrated that the yield gained from irrigation ranged from 4 to 5 t ha⁻¹ in very dry crop-year (drought) and 1 to 2 t ha⁻¹ in average year, while in wet years with high levels of rainfall, benefits of irrigation was negligible (0-0.4 t ha⁻¹). According to Pepó & Sárvári (2013), maize yield can be sustained between 11 to 12 t ha⁻¹ with appropriate levels of nutrient and water-supply, irrespective of the crop-year's effect in the maize production system on chernozem soil.

Hybrid maturity length can affect water use. According to Stone et. al (2006), earlier maturing hybrids tend to have lower yield and the water demand is also lower, in some cases, as much as 4 to 6 inches less. They posited that there is a compromise between water costs, yield and other factors of production which must be taken into consideration when selecting the maturity duration of hybrid.

In a four-years study, Lamm et al. (2009), found increasing maize population from 55,600 to 85,300 plants ha⁻¹, generally increased grain yield, and even without in season irrigation, the yield penalty was not significant at the higher density. The effects of weather-related stress could be mitigated with hybrid specific agro-technique (Széles et al., 2019).

Huynh et al. (2019) found irrigated maize consistently had better and more stable yields than rainfed, irrespective of tillage systems or crop rotation. Similarly, Rahman et al. (2015) and Abdellatif et al. (2016), found irrigation had significant effect on growth and yield parameters of maize and it improves nutrient uptake and utilization.

Pepó et al. (2008) reported that without irrigation, the negative effect of inadequate moisture availability was further exacerbated with the application of higher fertilizer rate and increase in planting density. Several literatures have confirmed that on an average the total amount of water that needed for maize during the cropping period vary from 500 to 600 mm, depending the prevailing weather, planting density, fertility status of soil, soil type and maturation duration for the specific hybrids.

Post-planting moisture stress can affect maize development and lower the yield potential. The extent of yield loss is dependent on the growth stage of the corn at the time of moisture stress and the crop is most sensitive to water stress during the flowering period. Spitkó et al. (2014) found that flowering synchrony was significantly affected by both the year and rainfall deficiency and length of proterandry was shorter in favorable year under irrigated condition (ranged from 0.25-3 days) compared to drought-stress year (ranged from 0.25-6 days). Ross et al. (1996) posited that water deficit stress at silking stage can impede development, resulting in shedding of pollen before the silks emerge and hence, poor or no pollination with extremely low yields. They found yield reduction prior to tasseling ranged from 10-20%, while tasseling to soft dough was 20-60% and soft dough to maturity, 10-35%.

In research conducted in Pakistan, aimed at improving the performance of maize hybrids with silicon fertilization under limited moisture supply, Amin et al. (2016), observed that moisture stress substantially affected the osmotic and leaf water potential of maize genotypes and silicon treated hybrids displayed improvement in drought tolerance under moisture stress condition. They posited that the harmful effect of drought can be mitigated through silicon nutrition, which induced several physiological changes, as it was found to significantly improve the growth and yield of the maize hybrids, in addition to being useful in minimizing the negative effects of water deficit stress.

Due to the time-consuming nature for the development of drought tolerant cultivar, Aslam et al. (2015), explored an alternative approach to screen cultivars for drought tolerance using morphological, physiological and biochemical indicators, as an alternative to final yield analysis in breeding programs. They screened the following hybrids for drought tolerance in early phases of their vegetative growth; FH-810, 32-F-10, FH-782, 32-B-33, YH-1898, Monsanto-6525, R-2315 and R-3304 with moisture treatments comprised of 100% field capacity (FC), 75% FC and 50% FC. They found the test hybrids varied in their stability response to drought stress and hybrid 32-F-10 exhibited the best drought tolerance compared to the other hybrids in terms of having the best plant height, leaf area and relative water contents, stomatal conductance, photosynthetic rate and transpiration. Hybrid YH-1898 was found to be highly drought sensitive, with the lowest values of those attributes in almost all water levels and the least gas-exchange values among all hybrids. They concluded that the findings of their research can be used to screen for drought tolerant-maize hybrids.

2.8.1 Effect of irrigation on yield of maize

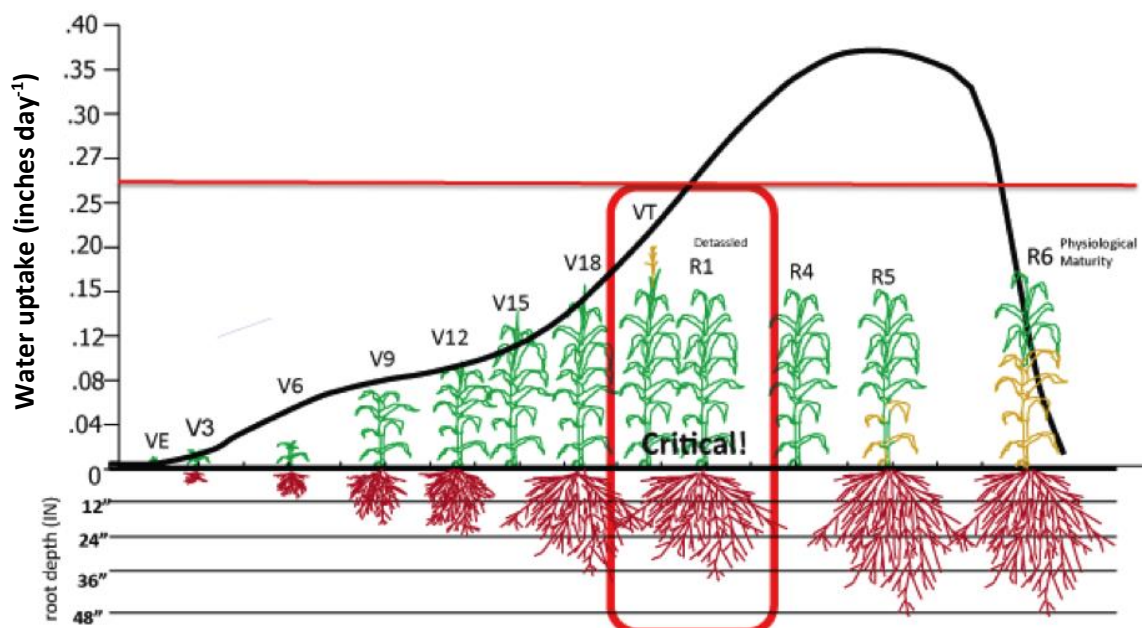
Both rainfall amount and distribution were found to have significant effect on maize yield. Nagy (2007), observed that poor yields are not always associated with drought conditions, but higher yields usually occur in favourable (wet) crop-years due to better soil moisture which facilitates improvement in fertilizer utilization. The effect of excess rainfall on yield is however dependent on the geographic location and in cooler region with inadequately drained soils and high pre-season soil water reserve, excessive precipitation can adversely affect yield (Li et al., 2019).

Nagy & Zeke (1982) found the moisture content of maize grain in many hybrids, was significantly increased by irrigation, especially in situation of low nutrient supply.

Irrigation significantly improves growth and yield parameters of maize, especially under moisture deficit condition (Rahman et al., 2015 and Abdellatif et al., 2016). Elias et al. (2014) observed that moisture deficit stress administered at some growth stages enhanced maize water use efficiency without any significant reduction in yield and water use efficiency was highest in maize supplied with 80 % of irrigation requirements (Abdellatif et al., 2016).

Dobos & Megyes (2013) analyzed yield of maize over a 10-year period and found 25-50% yield fluctuation was caused by the erratic precipitation and posited that irrigation is essential for security of yield and is not only an income improving intervention, but also serves to enhance market competitiveness. Results of long-term experimental have demonstrated that the yield increasement from irrigation varied with rainfall amount and distribution during the growing season. Vári (2013) found in dry years, irrigation significantly improved yield and posited that yield fluctuation could be mitigated through irrigation.

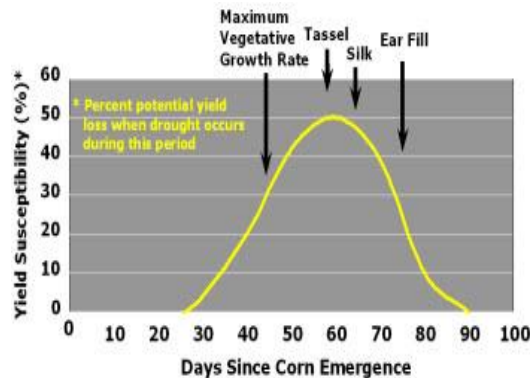
Maize has a transpiration coefficient of 350 L kg^{-1} dry material and the water demand during the growing season is 450-550 mm. Maize water requirement increases with growth and development of the crop and peaks during the reproductive phase. The intensive period of water uptake is in June and water supply during the flowering-fertilization (July) period is considered to be most crucial (fig. 12).



Source: <http://cropmetrics.com/2014/04/maximizing-root-zone-utilization-a-key-to-precision-irrigation-management/>

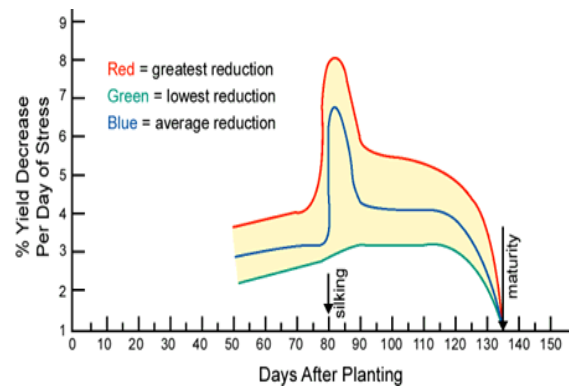
Figure 12. Maize water consumption during the growing season

Based on several research articles, yield loss due to moisture stress on the maize plant is most significant at tasseling (fig.13 a & b). Yield loss as a result of moisture stress during this period averages at 7% per day (fig. 13b).



Source: <https://www.pioneer.com/home/site/us/agronomy/library/corn-irrigation-mgmt-limited-water-supplies/#fig4>

Figure. 13a. Yield susceptibility of maize to water stress



Source: <http://agron-www.agron.iastate.edu/courses/Agro541/classes/541/lesson13a/13a.5.html>

Figure 13b. Moisture stress and yield loss in maize

Water stress can have detrimental impact on maize, resulting in reduced biomass and consequently yield. A major effect of water-related stress in corn is the delayed silking, which results in prolonged anthesis-silking interval, hence the main cause of yield failures (Maazou et al., 2016). They found that one day of moisture deficit stress during a week after silking reduce final yield by 8 percent and 3 to 4 days of extreme moisture deficit stress at this time can result 30% reduction in grain yield.

Khan et al. (2001) found that maize plant height, days to flowering, stem diameter and leaf area index decreased significantly with increasing moisture deficit stress. They also observed that yield components (grains per cob, 1000- kernel weight and grain yield) significantly decreased with increasing water stress. Irrigation prevents water stress situation and improves the efficiency of fertilization. The quantity of precipitation, or moisture reserve in the soil, reorients the uptake and utilization fertilizers. Wang & Xing (2017) demonstrated nitrogen fertilization and irrigation interaction had significant effects on biomass yield and harvesting index.

Water supply and fertilization mutually enhance the benefits of each other and influence yield, as well as the chemical composition of maize (Bocz & Nagy,1981). According to Nagy (1994), irrigation and fertilization are not independent of each other but interacts and the effect of fertilizer is enhanced as water-supply to the crop reaches optimum level and diminishes when the water-supply far exceeds the crop demand. The interaction

between water supply and soil fertility was very obvious in crop rotation systems and was found to be more pronounced in monoculture, when compared to bi and triculture.

Széles & Nagy (2020) found without irrigation, crop density values higher than 60–70 thousand plants ha⁻¹ resulted in 7–14% yield decrease. In study conducted at the Agricultural Research Institute at Martonvásár (Hungary) to identify genotypes with drought tolerance characteristics, Spitkó et al. (2014) found generally hybrids responded to moisture deficit stress with a reduction in the grain number, but some hybrids produced similar number of kernels per ear under dry conditions, compared to those in the control environment and can therefore be used to maintain high yield under water stressed condition due to their drought tolerant capability. In addition to grain yield, water supply was also found to influence starch and oil content of maize grains. Kresović et al. (2018) reported oil content of maize kernel was found to be highest with full irrigation and under rainfed conditions it was the lowest, while starch content increased, and oil content decreased with reduction in irrigation. Virág et al. (2020), however found irrigation impacted positively on starch and oil content, but differences were not statistically significant ($P>0.05$), whereas protein content was negatively affected by irrigation.

2.9 SELECTION OF GENOTYPES

Selection of maize hybrids is a critical agronomic management decision, since hybrids differ in their yield responses to changes in agrotechnology and agroecological conditions. The productivity of maize is dependent on the specific genetic makeup of the planted hybrid, coupled with favourable agroecological conditions and the adoption of adequate agrotechnology (Bernhard & Below, 2020; Tollenaar & Lee, 2002).

Higher yield is dependent on reducing plant stresses through breeding and selection, which promotes tolerance to higher seeding rate. Hybrids which respond positively to higher plant density will have a higher than average yield response to narrow row spacing and these tends to be the full season hybrids (Bernhard & Below, 2020). The prevailing weather along with the planting date and hybrid maturity, determines the length of the growing season (Baum et al., 2019).

More than 400 hybrids of maize are grown in Hungary and therefore offers a broad array to choose from. Based on the lines used in their production, hybrids can be categorized as, single cross, three-way cross and double cross hybrids (Pepó & Csajbók, 2013). The single cross accounts for approximately 80% of the sowing area in Hungary, due to the higher productivity and better heterosis effect.

According to Könczöl (2017), 73% of the twenty most popularly cultivated hybrids in Hungary belong to FAO 300 maturity group. Some hybrids responded positively to increase in plant density, while others yield less or showed no yield response to higher density (Murányi & Pepó, 2015). Maize hybrids have different vegetation periods which are important, since the growing degree days vary for the different regions of Hungary and also for facilitating the expansion of the harvesting dates.

According to Pepó & Csajbók (2013), in Hungary, traditionally, the length of the vegetation period is ranked by FAO number with the following groups:

- FAO 200-299 (very early maturing hybrids)
- FAO 300-399 (early ripening hybrids)
- FAO 400-499 (medium ripening hybrids) and
- FAO 500 and greater (late maturing hybrids).

Berzsenyi & Dang (2006) found that the plant population density of maize hybrids varies with each maturity group, depending on the FAO number. The stable planting density range being widest (50–90,000 plants ha⁻¹) in the lower FAO group (200–299) and as the maturation period extends with the higher FAO group, the stable planting density range narrows and moved towards lower plant densities. According to Djurović et al. (2014), medium-late hybrids had higher yields and response to favorable environmental conditions was superior, compared to hybrids with earlier maturation. Medium-early hybrids (FAO group 400) was the most stable within the evaluated range (FAO 300-700) and is more suitable for less favorable agro-environmental conditions and stressful environments (Djurović et al., 2014). Hybrids tolerance to environmental stress can be improved with higher levels of nitrogen fertilization (Széles et al., 2019).

Short-season genotypes have a lower yield potential in comparison to medium-late genotypes but displayed greater stability (Djurović et al., 2014; Nagy, 2007). The hybrids with shorter growing season require less growing degree days for maturation,

compared with full season hybrids. Nagy (2008) found mid-ripening hybrids in Hungary performed the best, but the yield increment was marginally higher (0.5 t ha^{-1}) than the early ripening hybrids, whereas the yield of late ripening hybrids was almost on par with early ripening hybrids.

Széles et al. (2019a) found longer maturing hybrid such as Armagnac (FAO 490) had greater efficiency in utilization of precipitation and fertilization compared to short maturity hybrid (FAO 320), hence the reason for the higher yield. The early hybrids (FAO200–300) can be produced at higher planting density, compared to the mid and late maturity hybrids which is susceptible to yield depression with increasing of density beyond the optimum level. Higher FAO number therefore requires less plants per hectare (Könczöl, 2017).

Hybrids phenotypic traits were found to correlate with grain yield, regardless of the plant spatial arrangements. Bernhard & Below (2020) found shoot biomass, harvesting index, 1000-kernel weight and total kernel were either strongly or moderately correlated with grain yield. Similar findings were reported by Mousavi et al. (2018).

Cultivating medium-late maturing hybrids of maize, under irrigated conditions with a high plant density of up to $10.5 \text{ plants m}^{-2}$ can significantly increase overall yield when it is combined with narrow inter-row spacing. The increase in yield, however, is a result of higher plant population since there is a reduction in grain yield per individual plant due to competition (stress) but increase in overall yield due to the higher density (Testa et al., 2016). Genotypes which are drought-tolerant have also been known to be tolerant to N deficiency (Bänziger et al., 2002).

One of the main challenges for improving maize yield is the identification of hybrids with both good yield potential and tolerance to a wide range of environmental conditions (Nielsen, 2010). According to Edmeades et al. (2017), temperate maize hybrids have a higher harvesting index (0.5–0.55), exhibit rapid ear growth, and have larger ears with approximately 500–600 kernels ear^{-1} in comparison to tropical hybrids, with a low-moderate kernels number (300–400) per ear and harvesting index, ranging from 0.25–0.40.

Genotype had significant influence on dry matter content, grain yields, grain starch and protein concentration, as well as starch and protein yield. Protein concentration of maize grain decreased with an increase in starch content and grain yield (Randjelovic et al.,

2011). According to Erdei et al. (2013), the selection of hybrids with the desired characteristics can be achieved through breeding program to meet the requirements as the raw material for food, feed or fuel. Selection is also important is disease control. According to Mubeen et al. (2017), Southern corn leaf blight is a fungal disease of maize plant that caused a noticeable reduction in crop yield and one of the most effective ways of controlling this disease is the selection of hybrids which are less prone to attack by the pathogen. In study conducted in India, Kaur & Kaur (2016), found genotypes can be use as breeding stock to enhance and produce nutritionally and nutraceutically enriched maize. They reported β -Carotene content among 30 test hybrids varied from 0.56–8.33 ppm with a mean value of 4.62 ppm, while two of the tested hybrids were found to be enriched in amino acids (tryptophan; lysine) which was otherwise generally low in maize.

Erdei et al. (2013) found that starch content ranged between 64.29–70.80% in lines and from 70.84–72.29% in case of hybrids, while the dry matter protein concentration ranged from 9.04–12.62% for parent lines and 7.61–9.56% in the single cross hybrids. They reported a strong correlation between thousand-kernel weight (TKW) and starch content, whereby the starch content was observed to increase as the TKW increased, but the oil content was unaffected, and the protein content decreased as both starch content and TKW increased. Simkó et al. (2020) found although the weight of kernel and ear were affected by N dosage and irrigation, the kernel cob⁻¹ ratio was more dependent on the genotypes.

Zhao et al. (2016) demonstrated that maize can be bred to enhance nutrient efficiency under deficient conditions. They showed maize inbred line 90-21-3, tolerance to K deficiency, by regulating the endogenous hormone content to alleviate K deficiency, thereby improving nutrient efficiency of maize under deficient conditions. According to Berzsenyi & Dang (2006), the interaction of genotype $\times$ environment is a major issue in yield trials since it reduces progress from selection and is statistically impossible to interpret the main effects. Maize yield is dependent on the genetic potential of a given hybrid, in addition to environmental influence and in-season management (Espinoza, 1996). According to Nahar et al. (2010), genotypes offer the advantage of not only higher yield but also in improving stability in production across various environmental conditions. They posited that in order to make crop production more economically viable, very adaptable, high yielding maize hybrids which can be produced at reasonable

costs can be bred by developing the ideal combination of parent lines with favorable traits.

Abdelmula & Sabiel (2007) reported that genotypes demonstrated different yield response, depending on the occurrence of drought on the growth stage. They observed that some genotypes were very tolerant to drought related stress when it occurred during the vegetative stage, whereas others, were more tolerant when the drought stress occurred during the reproductive phase. Veldboom & Lee (1996) posited that the various yield response of hybrids to moisture stress could be attributed to various sets of alleles and possibly different loci are being expressed under different ecological conditions.

Pepó (2014) opined that unfavorable abiotic stress effects can be mitigated with proper selection of genotypes and optimum levels of agrotechnical inputs. The selection of suitable genotypes will be of even greater importance in the future, as a result of climate change (Becze, 2014). The yield of a particular genotype is largely determined by its adaptabilities to the agroecological and agrotechnological conditions, and under optimal conditions, the yield amount is determined by the differences between the genotypes (Marton et al., 2005; Gardner et al., 1990).

3. MATERIALS AND METHODS

3.1 Experimental site and meteorological parameters

The research was conducted at the Látókép Research Station of the University of Debrecen, located in Eastern Hungary in the Hajdúság region (latitude 47°33' longitude 21°27'). The soil is classified as adobe (Arany plasticity index=43-45) and the soil type was calcareous chernozem soil with a near neutral pH ($\text{pH}_{\text{KCl}}=6.46$). The humus content of the soil is 2.3 % in the upper 20 cm of the profile and extends to a depth of approximately 80 cm, with good water holding capacity. The phosphorous and potassium supply of the calcareous soil average at 133 mg kg^{-1} (AL-soluble P_2O_5) and 240 mg kg^{-1} (AL-soluble K_2O), respectively.

The soil available water is estimated at 50% of field capacity. The minimum field capacity is 275 mm in the 0-1.0 m depth of the soil profile and 265 mm in 1.0 -2.0 m range of the profile.

Weather station on site, facilitated the daily recording of precipitation and temperature data which were then used to compute monthly total and average during the growing seasons of the examined crop-years (2018-2020). Mean monthly temperature and rainfall for the growing seasons of the studied period were compared with the 10-year mean (fig.14).

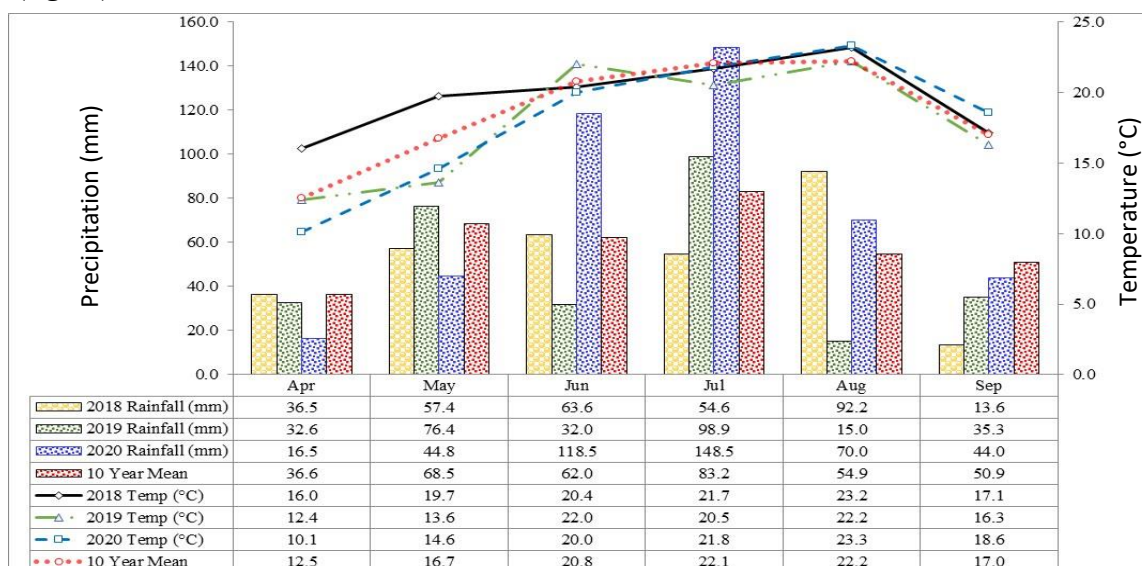


Figure 14. Monthly rainfall and average temperature vs. 10-year mean (Debrecen, 2018-2020)

Growing season rainfall (Apr-Sep) in 2020 (442.3 mm) significantly exceeded 2019 (290.2 mm), 2018 (317.9 mm) and the 10-year mean (355.9 mm). Temperature during the season (Apr-Sep) ranged from 16.0 - 23.2 °C in 2018, 12.4 - 22.2 °C in 2019 and 10.1

– 23.3 °C in 2020, compared to the 10-year mean of 12.5 – 22.2 °C. The highest growing degree days (GDDs) was recorded in 2018 (1,624), followed by 2020 (1,498) and 2019 (1,367).

3.2 Treatment combinations

Yield responses of three hybrids of maize, Armagnac (FAO 490), Loupiac (FAO 380) and Fornad (FAO 420) were investigated under different agronomic management conditions which include, three tillage treatments, two levels of plant densities, irrigated and rainfed (non-irrigated), three levels of fertilizer treatments and monoculture versus biculture (winter wheat forecrop) cropping systems (fig. 15).

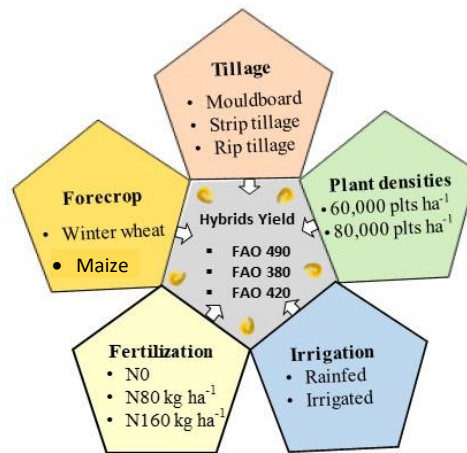


Figure 15. Schematic representation of treatment combinations

The area of each treatment plot was 30 m² (3m x 10 m) with 4 rows sown per plot. A control (N0 kg ha⁻¹) and two levels of nitrogen (N) make up the fertilization treatments (N0 kg ha⁻¹; 80 kg ha⁻¹; 160 kg ha⁻¹). Phosphorus (P) and potassium (K) dosages were the same for every plot (P₂O₅ = 60 kg ha⁻¹ and K₂O = 90 kg ha⁻¹). Thirty percent of the N dosage was spread in the autumn prior to tillage and seventy percent in the spring.

The treatments were as follows:

(a) Tillage

- Mouldboard plowing (MT): 30 cm depth. (fig 16a)
- Strip tillage (ST): 30 cm depth. (fig. 16c)
- Rip tillage (RT): 45 cm depth. (fig. 16b)

The main difference among the tillage treatments is the depth of tillth and amount of crop residues remaining on soil surface. The machinery and implements use for the tillage treatments are shown below in figure 16a-c. Due to stubble-stripping operation, the crop residue in strip tillage appears dispersed (fig.17).



Figure 16a. Moldboard tillage



Figure 16b. Ripper tillage



Figure 16c. Strip tillage



Figure 17. Tillage treatments crop residues, post planting operations (Debrecen, 2020)

(b) Fertilizer treatment levels

- Nitrogen (N)- 0 kg ha⁻¹ (control)
- Nitrogen (N)- 80 kg ha⁻¹ + P- 60 kg ha⁻¹ K- 90 kg ha⁻¹
- Nitrogen (N)- 160 kg ha⁻¹ + P- 60 kg ha⁻¹ + K- 90 kg ha⁻¹

Nitrogen (N) application was in the form of ammonium-nitrate (NH₄NO₃), P in the form of monoammonium phosphate (MAP) (NH₄H₂PO₄), while K application was in the form of Muriate of potash (KCl). The full dosages of P and K and 30% of the total N was applied in the autumn, while the remaining 70% N was applied in spring and incorporated in the soil during seedbed preparation.

(c) Plant density:

- 60,000 plants ha⁻¹ (mono)
- 80,000 plants ha⁻¹ (mono and biculture)*

* plant density in biculture plot was a standard 80,000 plants ha⁻¹, whereas, monoculture contained both 60 and 80,000 plant densities.

Sowing was carried out with a Gaspardo 6-row seeding machine, at an inter-row spacing of 76 cm and a sowing depth of 5 cm.

(d) Crop rotation:

- Monoculture maize (maize – maize)
- Biculture (maize -winter wheat (*Triticum aestivum* L) forecrop.

The winter wheat area (8.4 m x 262 m) in each of the three main tillage blocks in 2017 was rotated with maize in 2018 and the alternating sequence repeated in 2019 and 2020 (fig. 19).

(e) Irrigation:

- Irrigated
- Non-irrigated (rainfed)

Irrigation was applied in quantity which is close to the computed needs of the plant (273 mm) and demands of the prevailing crop-year. The equipment was a self-propelled, 75

cm division, Valley linear sprinkler irrigation system (fig. 18), guided by sensors which maintained uniformity in movement during operation.



Figure 18. Linear sprinkler irrigation system at Látókep Research Station (Debrecen, 2018)

3.3 Experimental design:

The experiment was setup in a split-plot design, at the Látókep Research Station. The experimental area was approximately 3 hectares, with a dimension of 122.7 m x 272.0 m and was equally divided into three main blocks, each with one of three tillage treatments (mouldboard-MT, strip tillage-ST and rip tillage-RT). The size of each tillage block was approximately one hectare (9,928 m²) subdivided into two sections, irrigated and non-irrigated without replication (fig. 19).

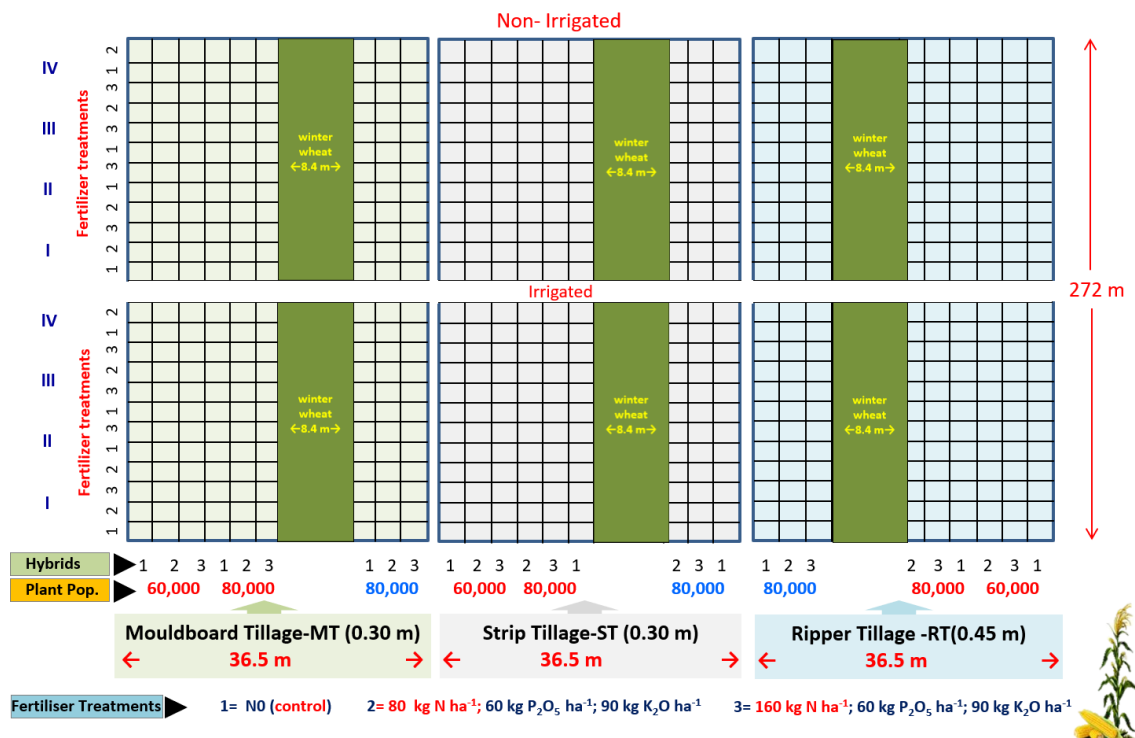


Figure 19. Split-plot experimental design

Each of the tillage treatment block was subdivided into two parts in a 1:4 ratio to accommodate winter wheat forecrop (biculture) and monoculture maize. The designated winter wheat area in each of the tillage treatment was approximately 20 % (8.4 m x 262 m) of the block area and was harvested in the autumn of 2017 and replaced with the three test hybrids of maize in 2018 spring. The hybrids (Armagnac -FAO 490; Loupiac-FAO 380; Fornad-FAO 420) were sown at 76 cm interrow spacing and a density of 60,000 and 80,000 plants per hectare in the main blocks, with monoculture plots having both densities, while biculture plots was a standard 80,000 plants ha⁻¹. The subplots of each tillage treatments were then subdivided to facilitate the application of three levels of fertilization (N0, N80, N160 kg ha⁻¹) with four random replications. There was a total of 216 subplots for each of the main blocks, and a total of 648 treatment plots (216 x 3) for the overall experiment. The crop was sown on 22nd April in 2018 and harvested on Oct 10th and the experiment was repeated through 2019 and 2020 with a variance of +/- 5 days.

3.4 Methodology and sequence of treatments application

Following harvesting of the experiment in 2017, stem crushing (stubble) of post-harvest crop residue commenced along with fertilization and disc tillage. Primary tillage operations were then carried out with the moldboard and ripper implements. Final preparation of seedbeds was completed in the spring, prior to sowing. The sequence of operations is summarized in table 1.

Table 1, Sequence of operations in maize production system (Debrecen, 2017-2020)

Moldboard plowing (MT)	Strip tillage (ST)	Rip tillage (RT)
Stem crushing (stubble)	Stem crushing (stubble)	Stem crushing (stubble)
Fertilizer application		Fertilizer application
Disc tillage	Disc tillage	Disc tillage
Moldboard Plowing (Autumn)	Strip tillage + fertilizer application	Rip Tillage (Autumn)
Secondary tillage (Spring)		Secondary tillage (Spring)
Seedbed preparation		Seedbed preparation
Sowing (April 22 nd +/- 4 days)	Sowing (April 22 nd +/- 4 days)	Sowing (April 22 nd +/- 4 days)
Weed control	Weed control	Weed control
Inter-row cultivator	Inter-row cultivator	Inter-row cultivator
Harvesting (Oct 10 th +/- 5 days)	Harvesting (Oct 10 th +/- 5 days)	Harvesting (Oct 10 th +/- 5 days)

3.5 Data collection

3.5.1 Soil parameters

In-season penetration resistance of tillage treatments were measured with a manually operated static cone penetrometer (Penetronik) integrated with moisture sensor until 0.65 m depth (fig. 20a). Soil moisture content of tillage treatments was monitored with capacitance probe in the range of 10-70 cm of the soil profile, with reading at 10 cm interval. Data collection commenced at sowing and continued fortnightly throughout the growing season (Apr-Sept) for each of the examined crop year (2018-2020).

Measurements of infiltration rates were carried out 6-8 weeks after planting in the inter-row of tillage treatments with a double ring infiltrometer and replicated three times in each tillage treatment. The specification of the infiltration rings was 20 cm (length) x 10 cm (internal diameter). A plastic liner was inserted inside the ring and a known volume of water was added. The liner was carefully removed, and the time was recorded. Infiltration water level of 10 cm was maintained in each ring and measurements were recorded at 10 minutes interval (fig.20b).

3.5.2 Growth parameters

Plant height, stem diameter and leaf area index (LAI) were measured at the tasselling stage (V_T) with the use of a measuring tape (fig. 20c). Two plants were randomly selected from each plot and the length and widest part of each leaf (width) measured using the method prescribed by Montgomery (1911) for LAI. The leaf area index was computed using the formula, $LAI = (L \times W \times 0.75)/0.167m^2$ for 60,000 plant ha^{-1} (ground area) and $0.125 m^2$ for 80,000 plants ha^{-1} .



Figure 20a. Penetrometer (Debrecen, 2020)



Figure 20b. Infiltrimeter (Debrecen, 2020)



Figure 20c. Plant height measurements (Debrecen, 2020)

Relative chlorophyll content of leaves in different fertilizer treatments were determined using the SPAD-502 (Konika Minolta) chlorophyll meter (fig. 20d). Measurement was carried out when the plants had eight fully developed leaves (V_8 stage).



Figure 20d: SPAD-502 Chlorophyll meter (Debrecen, 2019)

3.5.3 Yield Parameters

Cob length and circumference were measured with a carpenter's tape and 1000-kernel weight was determined by removing and weighing 100 grains from the middle section of four ears in 4 replications. Grain yield for each plot was ascertain at time of harvest by a built-in weighing unit on to the Sampo Rosenlew harvester (fig. 21).



Figure 21. Sampo Rosenlew – 2010 two-row harvester at Látókep Research Station

The harvester processed the cobs and separate the grains which are then weighed and recorded against treatment plot. Grain moisture of field samples were analysed using a GAC2100 electronic moisture tester. The moisture content was then computed 15% and the yield extrapolated to tons per hectare. Grain nutritional content (Starch, protein and oil) was determined using a FOSS InfratechTM 1241 analyser. The yield of starch, protein and oil per 100 g grain was then computed using FOSS data in the equation, $[(100/(100-a) \times b)]$, where a= actual moisture content and b= starch, protein or oil content of the sample at the given moisture content.

3.6 Statistical evaluation method

For economical analysis, the price of maize used was \$ 170 USD (50,000 HUF) per ton based on FAO data, while Nitrogen fertilizer was 190 Euro per ton (67,000 HUF) based on market price (<https://flagma.hu/en/fertilizers-o-1.html>). The conversion rate for nitrogen fertilizer required to produce one ton of grain was 25 kg (Nagy, 2006).

Fertilizer use efficiency (FUE) and Agronomic N efficiency (AE) was determined as follows:

- (i) Fertilizer use efficiency (FUE)= [Grain yield (kg)/applied fertilizer (kg)]
- (ii) Agronomic N efficiency (AE) = [Grain yield of fertilized plot (kg) - Yield of control (kg)] / Nitrogen fertilizer applied (kg)

Water use efficiency (WUE) for rainfall was computed as follows:

WUE (Rainfall) = [Grain yield in non-irrigated plots (kg)/ Growing season rainfall (mm)].

Analysis of variance (ANOVA) and test between subjects' effects was carried out on the different agronomic management factors (tillage, fertilization, irrigation, plant density, hybrid and crop rotation) to determine their effect on the yield of maize. Experimental data were analysed with Microsoft Excel, SPSS 26.0 and Genstat 18th edition programs. Statistical relationship between variables were determined using Pearson's correlation coefficient. The effect size and comparison of variables was performed with the ANOVA test and the Least Significant Difference (LSD) set at 5%, with all values less than 0.05 being considered statistically significant.

4. RESULTS AND DISCUSSION

4.1 Crop-year effect on yield (rainfall & temperature)

Growing season rainfall (GSR) in 2020 significantly surpassed that of 2018 and 2019 (fig.22), particularly during the peak water-demanding period of the growing season

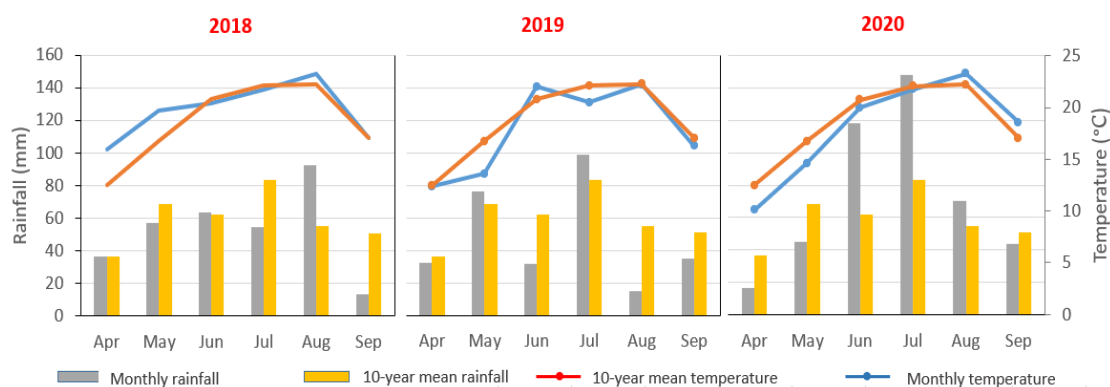


Figure 22. Growing season rainfall and temperature vs. 10-year mean (Debrecen, 2018-2020) (June-Aug). Summer rainfall (Jun -Aug) in 2020 exceeded the 10-year mean by 68% (137mm), and both 2018 and 2019 by 60% (127 mm) and 131% (191 mm) respectively. Thus, 2020 was the most favorable crop-year in terms of water supply, followed by 2018 and 2019 (2020>2018>2019).

Maize yield in 2020 was the highest (10.75 t ha^{-1}) and surpassed 2018 (10.35 t ha^{-1}) and 2019 (10.15 t ha^{-1}) by 4 and 6% respectively. The highest yield in 2020 is corroborated by findings of several researchers who observed in years with high levels of rainfall, yield surplus of maize was generally greater, and attributed it to the better water supply (Bramdeo & Rátonyi, 2020; Széles et al., 2018a; Pepó, 2008; Nagy, 2007). Butts-Wilmsmeyer et al. (2019), however, found that excessive rainfall early in the growing season led to yield reduction, resulting possibly from the leaching of nitrogen (fertilizer) from the soil environment. According to Bramdeo & Rátonyi (2020) and Nagy & Széles (2018), in addition to rainfall amount, the distribution is also an important yield affecting factor.

Weather is known to influence crop growth and development through material transformation and nutrient uptake, since it regulates moisture supply and heat of the crop environment (Kovács, 1982; Nagy, 1996). According to Nagy (2003), a positive correlation exists between rainfall and yield, hence, in years with good water supply (precipitation), the yield increasing effect of fertilizer is greater due to better utilization.

Wang et al. (2020) found the application of nitrogen fertilizer significantly increased grain yields of maize by 26.8% during favorable (wet) year, whereas in dry year the yield increase was a mere 5.4%. Similarly, Berzsényi (2010) also reported a very substantial effect of the year on yield and found wet years (GSR=337 mm) yield was 2.4 t ha⁻¹ greater than the dry years (GSR=227 mm), while Nagy & Széles (2018), reported a higher yield increment of 2.142 t ha⁻¹ in wet years, compared to dry years.

In addition to its influence on grain yield, weather condition of the crop-year also affects the grain quality (protein, starch, oil). High temperatures during flowering and grain fill due to drought and heat stress reduced starch deposition and oil content (Butts-Wilmsmeyer et al., 2019), while the grain protein concentration generally increases under dry conditions (Széles & Nagy, 2012; Ohio University extension service, 2018; Butts-Wilmsmeyer et al., 2019).

Despite 28 mm (10%) higher rainfall in 2018 compared to 2019, a test of significance (5%) between mean yield of the examined crop-years revealed no significant difference between the two years (table 2). The non-significant yield difference between the two years could be attributed to the better distribution in 2019, especially in July (fig. 22).

Table 2. Duncan's multiple range test of crop-year mean yield (Debrecen, 2018-2020)

Yield (t ha ⁻¹)				
	Year	N	Subset	
			1	2
Duncan ^{a,b}	2019	648	10.152	
	2018	648	10.348	
	2020	648		10.746
	Sig.		0.253	1.000
The error term is Mean Square (Error) = 9.545. a. Uses Harmonic Mean Sample Size = 648.000. b. Alpha =0.05.				

This observation is supported by findings of Bramdeo & Rátonyi (2020) and Nagy & Széles (2018), that in addition to the total amount of rainfall, its temporal distribution was also a substantial yield affecting factor and July was the most critical month. According to Lobell & Burke (2008), precipitation and temperature are the two most important climatic factors affecting maize production. Temperature variation during the growing season in 2019 was most erratic and sub-optimal in the early growth stage and is reflected in the low growing degree days (fig.23).

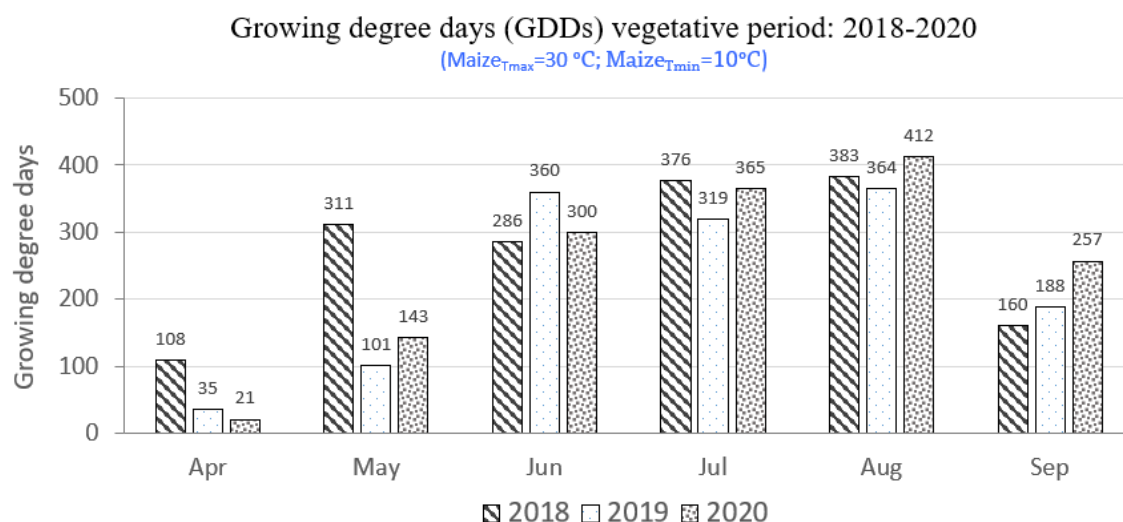


Figure 23. Growing degree days (Apr-Sep) for the examined crop years (Debrecen, 2018-2020)

According to Pepó & Csajbók (2013), maize needs 1100-1450°C useful heat sum (GDD) during the vegetative phase and temperature was most important from sowing to flowering. Heat units are involved in several physiological processes of the plant such germination, growth and development, physiological maturity and yield (Theivasigamani et al., 2013). The highest GDD (1,624) was recorded in 2018, which also had the most ideal condition for germination, compared to 2019 (1,367) and 2020 (1,498). Several researchers have observed that maize grain yields are reduced with higher temperatures in the summer, whereas, yields are increased with lower spring and higher summer rainfall (Wilhelm & Wortmann, 2004; Pepó & Csajbók, 2013; Nagy, 2006). Mean temperature during the summer months (Jun-Aug) was 21.8°C (2018), 21.6°C (2019) and 21.7°C (2020), all of which falls within the ranged of 21-27 °C for optimum yield, as described by Dobos & Megyes (2013). Growing-season rainfall positively correlated with yield (fig. 24a), whereas growing season temperature showed a negative correlation with yield during the examined period (fig. 24b).

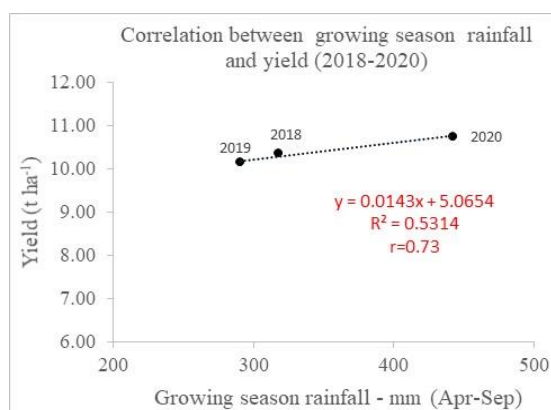


Figure 24a. Correlation between growing-season rainfall and maize yield (Debrecen, 2018-2020)

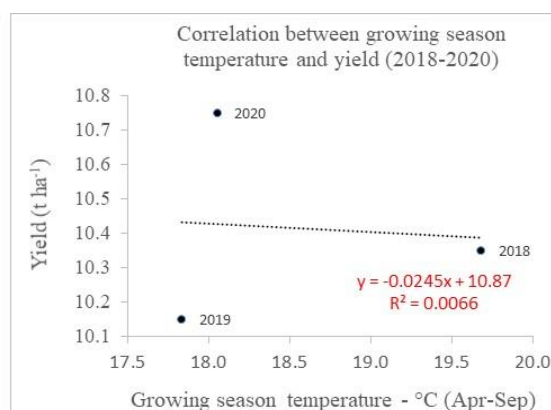


Figure 24b. Correlation between growing-season temperature and maize yield (Debrecen, 2018-2020)

Although three years of weather data in this research may be sub-optimal to meaningfully conclude on the correlation between weather and yield, it certainly provides an indication which concurred with results of long-term experiments. Bramdeo & Rátonyi (2020) made similar observation which showed annual precipitation (Oct-Sep) correlated moderately with yield ($r=0.68$), whereas, rainfall during the growing season (Apr-Sep) revealed a stronger correlation ($r=0.76$). Analysis of rainfall data showed June had the strongest correlation with yield, followed by July. This finding is however a deviation from results of long-term experiments which showed July had the strongest correlation with yield. The deviation from July in this research could be attributed to the small sample size (3 years) and the skewness of the 2020 crop-year.

Zdeněk et al. (2017), found July was the most important month for rain-fed irrigation and this was followed by August. They reported that precipitation accounted for 64% of the yield variability. Similarly, Huzsvai & Nagy (2005) found maize yields were closely correlated with the water content of the soil in July, followed by that in May, since it coincides with the most critical phenological phase of the maize plant (flowering) and moisture deficit at this time can result in significant yield loss (Nagy, 2012; Hodges, 1931).

Song & Jin (2019), however found severe moisture deficit during the early emergence stage (seedling) was more detrimental to growth and development than stress applied at heading and grain-filling, since it impacted negatively on leaf area index (LAI) and biomass production as a result of reduction in photosynthetic efficiency, which extends to the flowering stage and ultimately reduced grain yield.

The negative correlation between growing season temperature and yield is also consistent with findings of Hatfield & Dold (2018), Hatfield & Prueger (2015) and Lizaso et al. (2018), that maize productivity is reduced by extreme temperature ($> 30^{\circ}\text{C}$) in July, since it coincides with the flowering and pollination phase and is exacerbated when there are water deficits.

Crop-year accounted for 1.1% yield variance during the examined period and was statistically significant ($P<0.05$) but was relatively low compared to 11.0% in long-term experiment (Nagy & Pepó, 2015) and could be attributed largely to the absence of any extreme weather (drought) during the studied period.

4.2 EFFECT OF TILLAGE PRACTICES ON SOIL PHYSICAL PROPERTIES

4.2.1 Soil moisture

Tillage practices impacted on soil physical properties to varying extent. Soil moisture content in ST was 27% higher than MT and 18% above RT in the 0-30 cm range. In the lower soil profile (60-70 cm) RT moisture content exceeded ST and MT by 4 and 22% respectively. There was no significant difference in soil profile moisture between RT and ST in the in 0-20 cm range. However, both ST and RT moisture content were significantly higher ($P<0.05$) than MT (fig. 25).

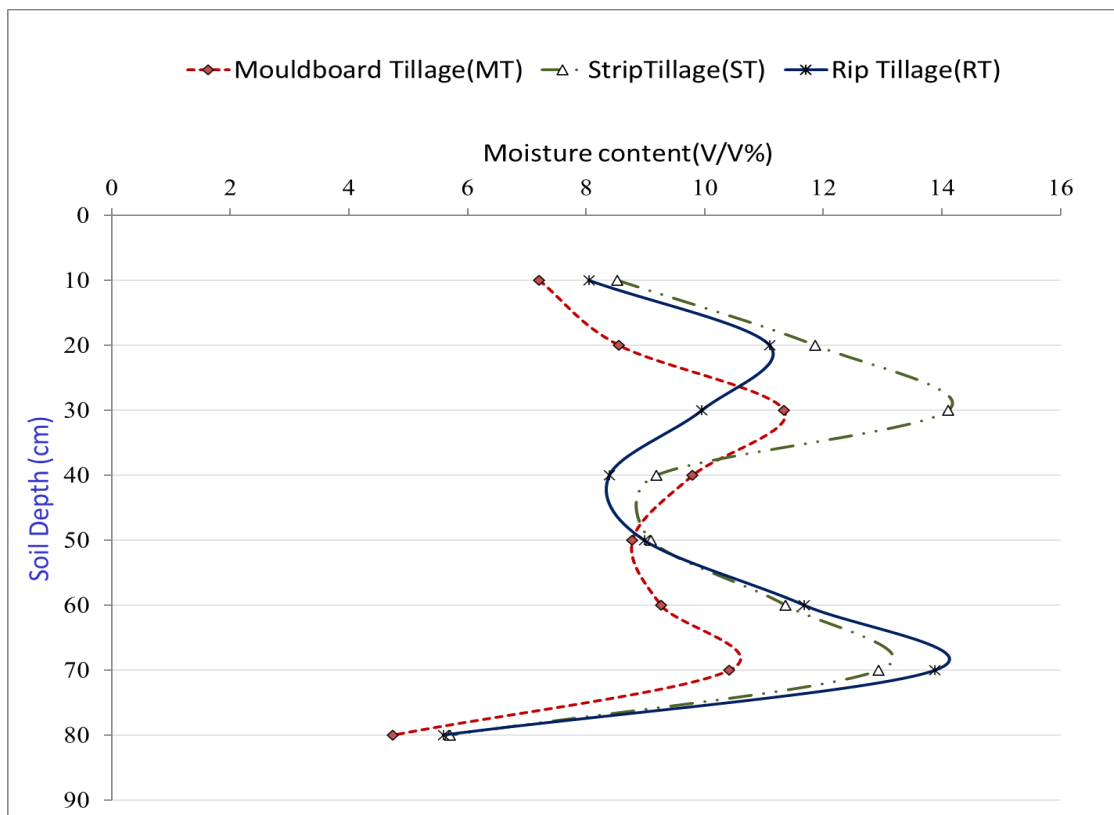


Figure 25. Tillage treatments and soil moisture content (Debrecen, 2018-2020)

Similar observations were made by Lamm et al. (2009), Acar et al. (2017), Roger et al. (2007) and Rátonyi et al. (2018), who found that soil moisture content under reduced tillage were higher in comparison to conventional tillage practices. Copec et al. (2015) also reported similar results, which showed a very strong correlation ($r = 0.97$) between soil water content and tillage systems. ST contrast to MT with significantly higher crop residue (>30%) on the soil surface also. The lower moisture of MT could be attributed to the inversion of crop residues and pulverization of the furrow slice which increases moisture loss (Vyn & Raimbault, 1992; Drury et al., 2004).

4.2.2 Infiltration rate of soil in tillage treatments

Analysis of soil infiltration rate in tillage treatments showed significant differences among treatments. The highest infiltration rate was recorded in RT inter rows (4.55 cm hr^{-1}), followed by MT (3.59 cm hr^{-1}) and ST (3.01 cm hr^{-1}) (fig. 26). Rates of infiltration

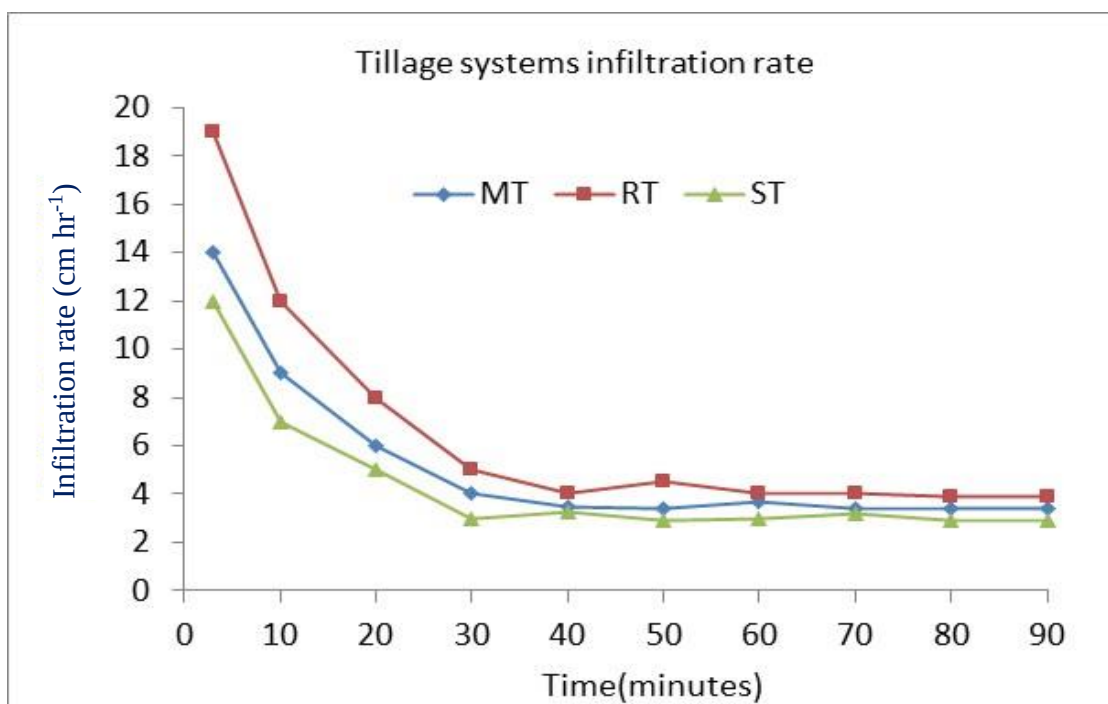


Figure 26. Tillage treatments and infiltration rate (Debrecen, 2018-2020)

decrease with time and after 40 minutes, differences in infiltration rates among tillage treatments were not statistically significant ($P < 0.05$).

According to Fan et al. (2013), infiltrability is an important soil physical property, which affects soil water availability for plant use. In similar research, Hussein et al. (2019), reported highest infiltration rate in deep tillage (245 mm hr^{-1}), followed by conventional tillage (129 mm hr^{-1}), and non-till (117 mm hr^{-1}). Similar report by Khan et al. (2017), showed the lowest infiltration rate was recorded in minimum tillage plots, while the highest infiltration rate was observed in conventional tillage practices, followed by deep tillage treatment. Report by Blanco-Canqui et al. (2017), however, showed no significant difference in infiltration rate among tillage treatments (non-till, chisel plow, moldboard), although they observed the highest infiltration rate in moldboard tillage. On the contrary, Fan et al. (2013), reported lowest infiltration rate in moldboard tillage (MT), compared to non-till (NT) and attributed it to more biological macro-pores which occur in NT soil than in MT. The variation in results of infiltration rates for the

various tillage systems could be attributed to differences in physical properties of the soil (texture, moisture, structure), type of tillage implements, ground cover and agroecological conditions, all of which can influence the rate of infiltration.

4.2.3 Penetration resistance of soil in tillage treatments

The effects of tillage practices on soil penetration resistance was significant in the 0-50 cm range (fig. 27). Penetration resistance in ST was significantly higher than MT and RT. Mean penetration resistance in ST inter-rows in the 10-30 cm range was 1.2 MPa, which was 85% higher than MT (0.65 MPa) and 41% above RT (0.85) treatments.

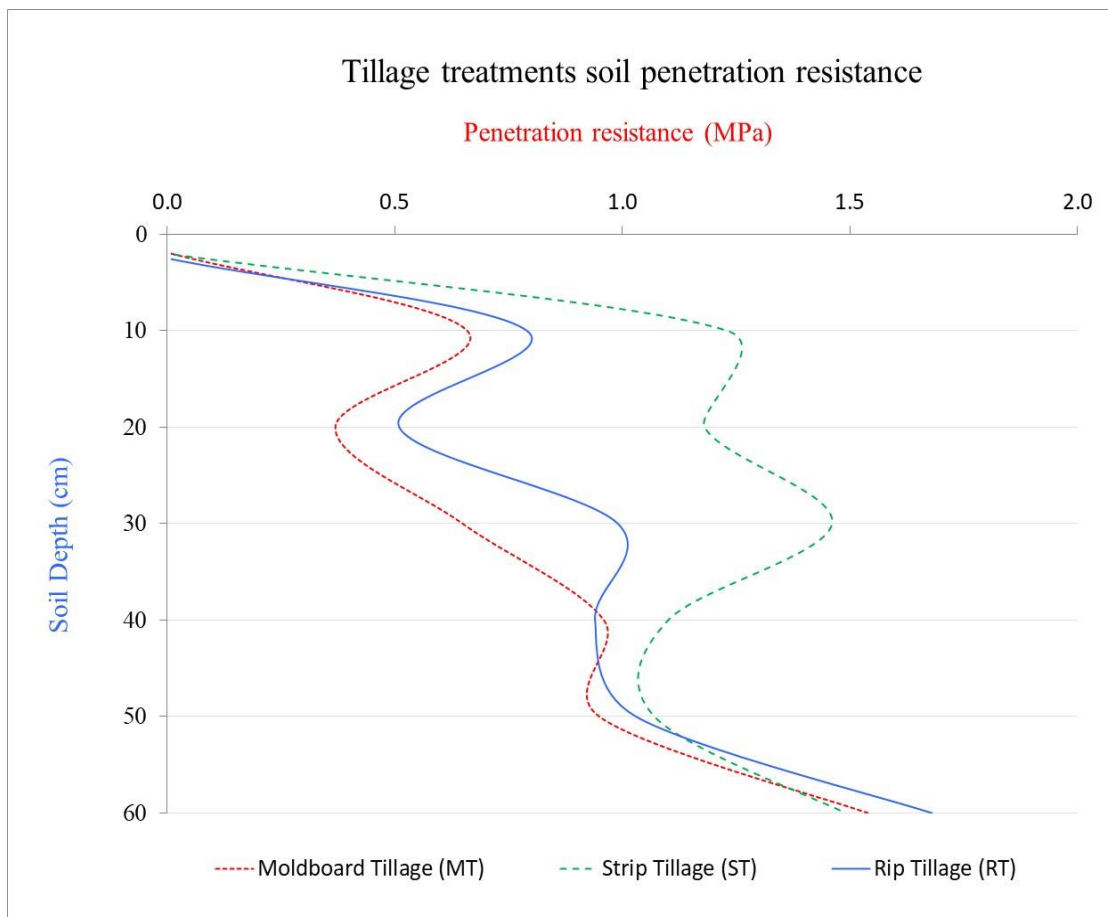


Figure 27. Effect of Tillage treatments soil penetration resistance (Debrecen, 2018-2020)

Similar results were reported by Bramdeo & Rátonyi (2020), Lin et al. (2016), Wang et al. (2015) and Jabro et al. (2010), who found soil penetration resistance in conventional tillage (MT) and deep tillage was significantly lower than reduced and no-till. Lin et al. (2016) also observed that with increase in soil penetration resistance, maize root mass densities was significantly reduced, as a result of which, grain yields were affected.

4.2.4 Effect of tillage practices on germination, growth and yield parameters

Based on observation, germination of maize seeds was earliest in MT, followed by RT and was more pronounced in the biculture plots of all tillage treatments. Delayed germination was very evident in ST (fig. 28), as a result of which there were significant



Figure 28. Maize germination in ST (left) and MT (right) four weeks after sowing (Debrecen, 2020)

differences in plant height in the early growth stage (fig. 29).

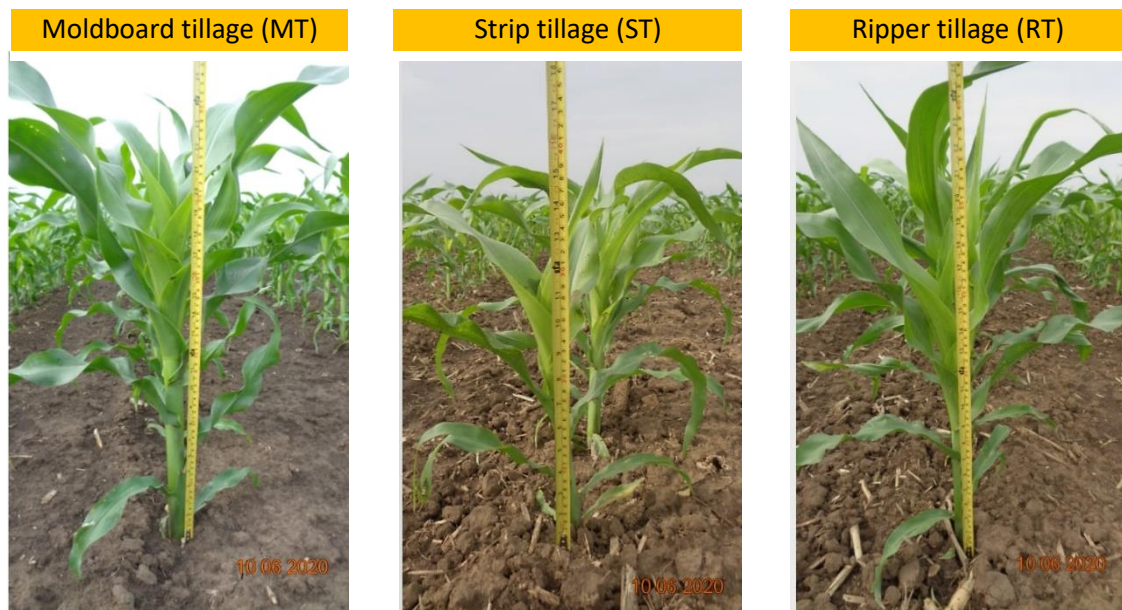


Figure 29. Maize plant height in tillage treatments, 45 days after sowing (Debrecen, 2020)

The lowest germination count was recorded in ST (85.0%), while germination in MT (96 %) was highest. There was no significant difference in germination percentage between MT (96%) and RT (94%). Amongst the three tillage treatments, ripper tillage (RT) produced the tallest plants (229 cm), with the highest 1000 kernel weight (378 g) and grain yield (11.00 t ha⁻¹), followed by moldboard (MT); plant height (222 cm);

1000 kernel weight (374 g); grain yield, (10.32 t ha⁻¹). Strip tillage yield (9.93 t ha⁻¹), plant height (202 cm), 1000 kernel weight (348 g) was the lowest (table 3).

Table 3. Tillage treatments effect on growth and yield parameters (Debrecen, 2018-2020)

Tillage treatments	Measured parameters							
	Mean plant height (cm)	Mean stem diameter (cm)	Mean cob circumference (cm)	Mean cob length (cm)	Mean rows cob ⁻¹	Mean kernels row ⁻¹	Mean 1000 kernel weight (g)	Mean grain yield (t ha ⁻¹)
MT	222 ^b	2.6 ^a	17.3 ^b	19.9 ^a	17.4 ^a	37 ^a	374 ^b	10.32 ^a
ST	202 ^a	2.4 ^a	16.6 ^a	19.7 ^a	17.6 ^a	37 ^a	348 ^a	9.93 ^b
RT	229 ^b	2.8 ^b	17.7 ^b	20.3 ^a	17.0 ^a	36 ^a	378 ^b	11.00 ^c
LSD _{0.05}	Values with different letters in column differ significantly (P<0.05)							

Similar results were reported by Anjum et al. (2019) and Wasaya et al. (2017), who found that maximum grain yields, number of kernel per cob, 1000-kernel weight and plant height were obtained from maize hybrid in deep tillage treatment, while conventional tillage was the second best. The result is also consistent with report by Vyn & Raimbault (1992), who found that plant growth was delayed and average yields in strip tillage were lower than the moldboard tillage in silt loam and clay loam, by 10.3 and 12%, respectively. Drury et al. (2004), also found germination and emergence of maize with winter wheat forecrop was delayed by approximately 3 days in no-till treatment and was delayed only slightly in zonal tillage compared to moldboard tillage owing to difference in soil temperature among the tillage treatments. Similarly, Lamm et al. (2009), also observed earlier emergence and improved growth of maize under conventional tillage treatments, compared to no-till and strip tillage.

4.2.5 Effect of tillage practices on maize yield

Tillage practices accounted for 2% of yield variance during the examined period. The relatively small yield variance (2%) is a reflection of the good quality of the Chernozem soil at the experimental site and is supported by report of Nagy (1996) & Fenyves (1997), who found that on well-structured soil, the depth and method of tillage have no significant influence on yield of maize.

Tillage treatments yield fluctuated over the examined crop-years, ranging from 4 to 9% with MT being most stable (4%), followed by ST (5%) and RT (9%). Tillage x year interaction during the examined period was not statistically significant (P>0.05).

However, significant interactions between crop-year x tillage practices were reported by some researchers who found seasonal temperature and rainfall patterns of the year influences the effects size of soil tillage which is modified mainly by the various levels of water supply of the year (Nagy, 2006; Wilhelm & Wortmann, 2004; Cai et al., 2014). The influence of seasonal rainfall on tillage treatments was also observed by Bramdeo & Rátonyi (2020b), who found yield of tillage treatments correlated with growing season rainfall (GSR) to varying extent, with the strongest correlation in MT ($r=0.86$), followed by RT ($r=0.79$) and ST ($r=0.33$).

In 2019 with the least GSR, yield of ST (9.2 t ha^{-1}) in monoculture was on par with MT (9.2 t ha^{-1}), while in 2020 which was a relatively wet year, yield of ST was significantly lower (8.3 t ha^{-1}). Yield variation between tillage treatments was highest in 2020 (fig. 30a) with a RSD of 36%, followed by 2018 (RSD=28%) and 2019 (RSD=23%). Noticeable yield differences during the examined period for the same tillage practice, highlight the effect of crop-year. In 2019 with the least GSR, yield variation in MT was higher than both RT and ST, while in 2020 with the highest GSR yield variation in ST was highest (CV=40%) compared to RT (30%) and MT (36%).

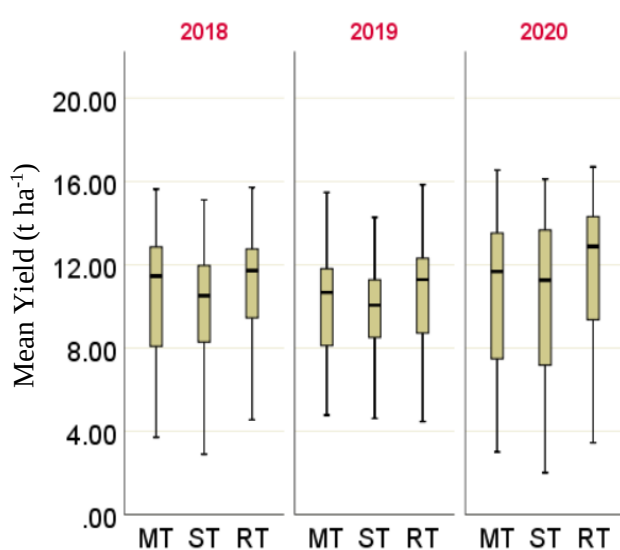


Figure 30a. Boxplot of yield x tillage treatments x year (Debrecen, 2018-2020)

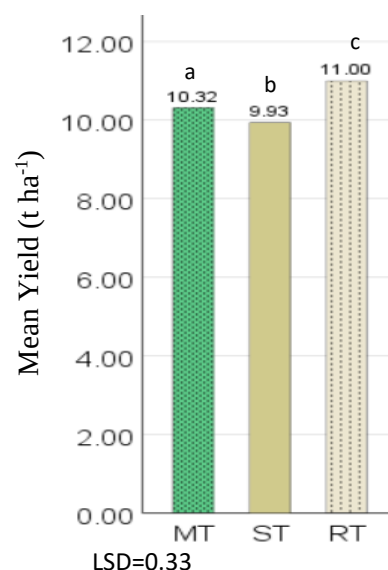


Figure 30b. Mean yield of tillage treatments (Debrecen, 2018-2020)

Mean yield of RT was 11.00 t ha^{-1} (fig. 30b) and was 7% (0.68 t ha^{-1}) higher than MT (10.32 t ha^{-1}) and 11% (1.07 t ha^{-1}) above ST (9.93 t ha^{-1}). The consistency in the order of performance of the tillage treatments (RT>MT>ST) was the same in each of the three examined years, with significant differences between treatments at the 0.05 level (table 4).

Table 4. Test of significance between tillage treatmentsDependent Variable: Yield (t ha⁻¹)

	(I) Tillage	(J) Tillage	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	MT	ST	0.381*	0.170	0.026	0.047	0.715
		RT	-0.681*	0.170	0.000	-1.015	-0.347
	ST	MT	-0.381*	0.170	0.026	-0.715	-0.047
		RT	-1.062*	0.170	0.000	-1.396	-0.728
	RT	MT	0.681*	0.170	0.000	0.347	1.015
		ST	1.062*	0.170	0.000	0.728	1.396

The error term is Mean Square (Error) = 9.413. *. The mean difference is significant at the .05 level.

Analyzing yield over a five-year period (2015-2019), Bramdeo & Rátónyi (2020) found overall yield differences between ripper (RT) and mouldboard tillage (MT) was not significant ($P>0.05$), however compared to strip tillage (ST), both RT and MT were significantly ($P<0.05$) higher. The findings of this research however differ in the level of statistical significance between RT and MT and could be attributed to the effect of the crop-years during examined period, since all other independent variables were held constant.

Several researchers have reported similar findings which showed that grain yields were significantly affected by soil tillage systems and deep tillage (RT), generally produce higher yields, compared conventional and minimum tillage. The higher yield of RT (7-11%) concurred with the findings of Schneider et al. (2017), who after analyzing data from 67 experimental sites reported that deep tillage on average slightly increased yield (+6%). They found that the effects of deep tillage were highly site-specific and at locations with root-restricting layers, yield increase was 20% higher than at locations without root-restricting layers.

Research by Anjum et al. (2019) also showed that maximum grain yield (7.20 t ha⁻¹) was obtained under deep tillage, while conventional tillage was the second best, with yield of 6.68 t ha⁻¹, followed by minimum tillage (4.60 t ha⁻¹). The yield difference between deep and conventional tillage (7.8%) as reported by Anjum et al. (2019), and the order of yield increase is also consistent with the results of this research, (RT=deep tillage>MT=conventional>ST=minimum). In China also, Feng et al. (2018), found grain yield were significantly affected by tillage systems and average grain yield of maize increased by 693 kg ha⁻¹ (6.3%) under subsoil tillage (RT), compared with those under

rotary tillage. Similar report by Yu et al. (2019), showed subsoil tillage significantly increased the number of kernels per spike and their 1000-kernel weights in all planting densities of maize hybrids. In Pakistan, Wasaya et al. (2018) reported higher grain yield was obtained in maize grown under chisel plow (RT) compared to moldboard (MT). Results by Khan et al. (2017) have also demonstrated that deep tillage grain yield was 10.99% higher, as compared to minimum tillage.

Wang et al. (2015) found that chisel plowing (deep ripping) lowers bulk density, increases total porosity, and had higher nitrogen uptake compared to moldboard and other conventional tillage. As a result, higher crop biomass and grain yield were obtained with deep tillage, in comparison to non-till and rotary tillage. They found that deep tillage enhanced root length density and improved moisture content of the soil in the 20–50 cm range of the profile, which led to increase in uptake of moisture and N by the roots in the lower profile. According to Feng et al. (2018), subsoil tillage increased maize yield as a result of improvement in soil conditions and roots elongation and distribution. Schneider et al. (2017), however, noted that deep tillage was highly site-specific and the risk of negative deep tillage effects was higher in soils with >70% silt. The successful use of deep tillage also requires soil moisture within the maximum tillage depth range to be below the plastic limit (Borchert, 1975; Eck & Unger, 1985).

The superiority of MT over ST was also observed by Habtegebrial et al. (2007), who found the highest biological yield of maize was obtained with conventional MT compared to minimum tillage and non-till. The lowest yield in ST is also consistent with findings of Doren et al. (1976) and Uri (2000), who reported that maize grain yield was lower in minimum tillage, compared to conventional tillage. Several researchers have however reported otherwise, which leads to the conclusion that the effect of tillage practices on yield of maize is influenced by the weather conditions of the crop-year. Under drought condition, the yield of minimum tillage was found to be higher than conventional tillage. In 2012 which was a relatively dry year in Hungary, Ferencsik & Rátonyi (2014) observed yield of strip tillage was significantly higher than moldboard tillage (MT) and almost on par with ripper tillage (5.68 vs 5.42) (ST>RT>MT). Similarly, in Kansas, USA, report by Lamm et al. (2009) showed strip tillage produced significantly higher yields than conventional tillage in both 2005 and 2006 and had less variation in grain yields than conventional tillage, especially during dry years. In Serbia also, Simić et al. (2020) reported that in dry years, maize yield was higher under reduced

than conventional tillage. Similar studies conducted in Guinea savanna zone of Ghana, showed grain yield of maize was 68% higher in non-till compared to conventional tillage due to better water conservation and weed control in non-till compared with conventional tillage (Buah et al., 2017). Roger et al. (2007) also observed under persistently dry conditions maize cultivated with strip tillage performed better than those planted with conventional tillage due to better moisture conservation. In growing seasons with dry spells, the benefits of deep tillage were found to be higher than in average years (Schneider et al., 2017).

Findings by Vyn & Raimbault (1992), revealed that on clay loam soil, there was no significant difference between ST and chisel plow, and on sandy loam, ST yields were significantly lower than the MT treatment in 1 out of 3 years, while it was equal to chisel plow in all 3 years. They also noted that the type of strip tillage implements influences soil tilth and crop growth and found Howard Rotaspikes and Rotavator compare most favorably with MT than Lely Roterra and strip-till cultivator. Similarly, Nassir (2018), found that the type of moldboard plow (helical, semi-helical, general purpose) and tractor speed influence soil physical properties to varying degrees.

After evaluating five different tillage practices (direct planting, disking-disc-harrowing at 16-20 cm depth; plowing at 22-25 cm depth; medium deep loosening at 35-40 cm depth plus disc tiller at 16-20 cm depth; medium deep loosening at 35-40 cm depth plus plowing (22-25 cm) in Hungary, Fenyves (1997) concluded that the combination of plowing and deep loosening was the most favorable in maize production system. Similar findings by Birkás et al. (1999) showed that maize yield after disking combined with loosening was 42% greater over 7 years average, and 20% greater over 3 years average, than after shallow disking alone. They observed that the regular application of soil loosening after disking also proved helpful in control of weeds, though not as effective as that of regular plowing. In Japan however, Shinoto et al. (2020), found tillage methods had no significant effect on maize yield. Even though they observed significant differences in the early stages of growth, the differences were not significant in latter stages and grain yield was also not significantly different.

Based on the results of the tillage treatments (RT>MT>ST) in this research and findings as reported by other researchers globally, it is evident that tillage practices are generally influenced by the weather conditions, types of tillage implements, soil types and the

successful implementation of tillage systems largely depends on the location and physical properties of the soil such as texture, moisture, bulk density, etc. In Hungary, the prevailing semi-arid type of climate would necessitate a tillage system which can conserve on soil moisture, while simultaneously allowing for the achievement of sustainable yield in maize production system. Each tillage practice has its advantage and disadvantages in terms of soil moisture conservation, yield, costs, and environmental benefits. The choice and implementation of tillage practices therefore require a holistic approach since fuel consumption, machine productivity, time and labour, as well as the impact on the environment are all likely to vary, in addition to the yield, hence, the tillage system with the highest yield may not necessarily imply sustainability of the practice. Several researchers are also of the view that the effects of tillage systems on yield of maize cannot be evaluated on a short-term basis (single season) and several years are required to adequately adjudged the system.

4.2.6 Tillage system costs, yield and environmental benefits

The three tillage systems costs (inclusive of sowing, stubble and fertilizer) ranged from a 232,741 to 249,092 HUF (table 5). MT costs exceeded both RT and ST by 2% and 7% respectively. The lowest cost per kilogram grain was achieved with RT (table 5).

Table 5. Tillage system costs, grain yield and costs kg⁻¹ (Debrecen, 2018-2020)

Tillage System	Costs ha ⁻¹ (HUF)	Grain yield (t ha ⁻¹)	HUF kg ⁻¹ (grain)
MT	249,092	10.32	24.14
ST	232,741	9.93	23.44
RT	244,605	11.00	22.24
Mean	242,146	10.42	23.24

The relatively low costs ha⁻¹ of ST compared to conventional tillage system was widely reported in Hungary (Husti et al., 2016, Kristo et al., 2013, Birkás et al., 1989), as well in the USA where it originated.

Yield of RT was 11% (1.07 t ha⁻¹) higher than ST, while the cost ha⁻¹ was also 5% (11,864 HUF ha⁻¹) higher. The revenue earned from the incremental yield gain of RT (1.07 tons * 50,000 HUF ton⁻¹ grain= 53,500 HUF) can offset the increase costs over

ST. Thus, RT is a more economically feasible tillage system than ST. (Price of maize=170 USD (50,000 HUF) ton^{-1} (FAO STAT 2020). MT costs was 7% (16,351 HUF ha^{-1}) higher than ST and the yield gain was only 4% (0.39 t ha^{-1}). The marginal increase in yield of MT (0.39 tons * 50,000 HUF ton^{-1} grain = 19,500 HUF) over ST can still generate adequate revenue to offset the additional costs of MT. Thus, from an economic standpoint, MT is also a viable option over ST.

RT yield was 0.68 tons higher (6.5%) than MT and cost was 2% lower. Hence, RT is a more cost-effective alternative to both ST and MT. Given the need for sustainable crop production technology, consideration should also be given to the environment, in addition to the elements of costs and yield when determining the suitability of a tillage system. The impact of tillage practices on the environment is well documented (Birkás et al., 2017) and each system has its advantages and disadvantages which is well illustrated in figure 31. None of the three tillage systems excelled simultaneously in yield, costs and environmental benefits. ST with the greatest environmental and cost benefits recorded the lowest yield. On the other hand, RT excelled in yield with moderate costs and environmental benefits, while MT with the least environmental and cost benefits, produced intermediate yield.

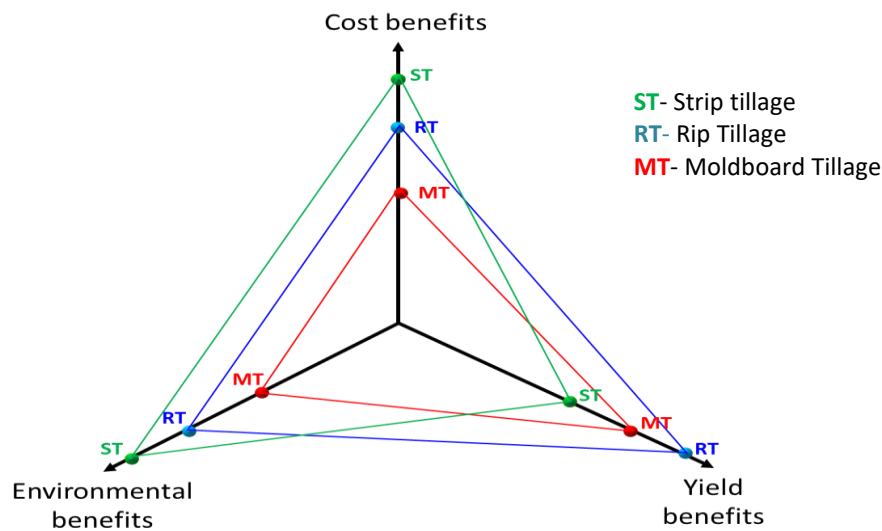


Figure 31. Performance of the three tillage systems (MT, ST, RT)

It can be concluded that RT is the best option of the three tillage systems owing to it higher yield, satisfactory environmental impact (moisture conservation) and moderate costs.

4.2.7 Tillage x forecrop interaction

Tillage x forecrop interaction was significant over the examined period. The yield of tillage treatments improved by 30-40% (3.01-3.61 t ha⁻¹) with winter wheat forecrop (table 6).

Table 6. Yield of maize (t ha⁻¹) by Tillage x forecrop x year (Debrecen, 2018-2020)

	Ripper Tillage (RT)			Strip Tillage (ST)			Mouldboard Tillage (MT)		
Year	*Mono	Biculture	Diff*	*Mono	Biculture	Diff*	*Mono	Biculture	Diff*
2018	9.78 ^a	12.66 ^a	+2.88	8.77 ^a	12.15 ^a	+3.38	8.98 ^a	13.27 ^a	+4.29
2019	9.97 ^a	11.98 ^b	+2.01	9.17 ^a	10.86 ^b	+1.69	9.16 ^a	11.94 ^b	+2.78
2020	10.23 ^b	14.36 ^c	+4.13	8.34 ^b	13.84 ^c	+5.50	9.20 ^a	12.96 ^c	+3.76
Mean	9.99	13.00	+3.01	8.76	12.28	+3.52	9.11	12.72	+3.61

*Mono- monoculture; Diff *- difference; (LSD 0.05=0.42; Values with different letters in column differ significantly)

In all three tillage systems and in all years, maize yield was significantly lower in monoculture, compared to biculture cropping system. The findings are in conformity with reports by several researchers (Bernivolja, 1976; Cramer, 1989; Berzsenyi, 2010; Sárvári, 1995, Vári, 2013).

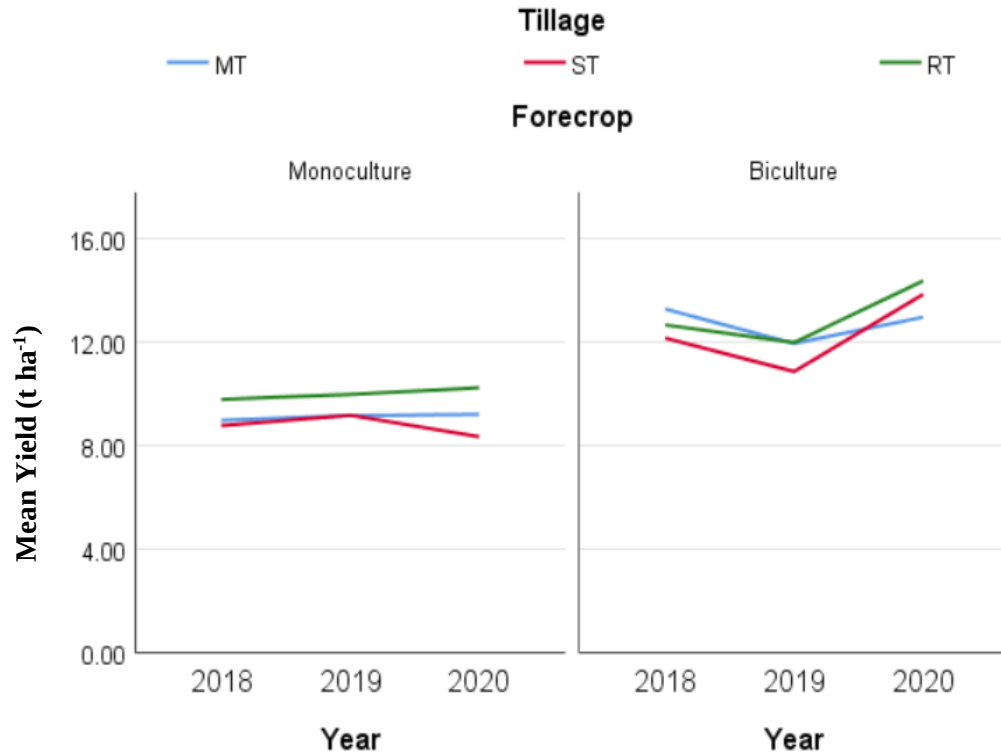


Figure 32. Year x tillage x forecrop interaction (Debrecen, 2018-2020)

In all the examined crop-years, yield of RT was consistently and significantly ($P < 0.05$) superior (10-14%) to MT and ST in monoculture cropping system (fig. 32), whereas in biculture cropping system the yield differential was reduced (2% - 6%).

ST and MT were more responsive to crop rotation than RT with a mean yield increase of 3.52 and 3.61 t ha⁻¹ respectively. There was no significant difference in yield between ST and MT in monoculture, however in biculture, the difference was statistically significant. Yield variations for tillage treatments were lower in biculture compared to monoculture (CV 14% vs. 32%).

AL-Kaisi et al. (2006) reported similar results in corn soybean rotation, which showed deep ripping yield was highest, 9.71 t ha⁻¹ (180.5 bu ac⁻¹), followed by MT- 9.61 t ha⁻¹ (178.7 bu ac⁻¹), ST-9.02 t ha⁻¹ (167.7 bu ac⁻¹) and non-till-8.95 t ha⁻¹ (166.4 bu ac⁻¹). Bramdeo & Rátonyi (2020) found that RT yield in monoculture was higher (5.5%) than MT and posited that the higher yield of ripper tillage over moldboard tillage in monoculture demonstrated its suitability for soil with lower nutritional status (monoculture), poorer structure (lower organic matter content), and higher bulk density, as compared to biculture. The shattering and subsoiling effect of RT is also known to reduce soil bulk density and increase the plant access to subsoil resources (Abidela, 2019; Al-Kaisi et al., 2015). Similar results on tillage x forecrop interaction were reported by Wilhelm & Wortmann (2004) and Roth (1996), who found that yield increased as a result of crop rotation, due to the enhancement of soil physical properties, such as the tilth and bulk density.

In corn-soybean rotation (C-S) and continuous corn (C-C), Al-Kaisi et al. (2015) found in some locations corn yield in ST was not significantly different from moldboard plowing (MT) and deep ripping (RT) under C-S rotation, while in other locations differences were significant. They concluded that for optimum yield to be realized, a location-specific tillage system and crop rotation is required.

It has been well established from the results, that regardless of the tillage system, yield of maize increase significantly in biculture cropping system. The results demonstrated that although ST yield was the lowest among the three tillage systems in monoculture, it can be significantly improved with winter wheat forecrop, as evident in table 6, where the yield of ST in biculture was 35% (3.17 t ha⁻¹) and 23% (2.28 t ha⁻¹) higher than MT and RT in monoculture, respectively. The result suggests that crop rotation can augment

the yield of strip tillage ST in maize production system. Similar reports by Douglas et al. (2013) and Sárvári (2005), showed that crop rotation can aid the successful implementation of minimum tillage and reduce the costs of production with fewer inputs.

4.2.8 Tillage x fertilization interaction

A positive interaction was observed between tillage practices and fertilizer treatments. Yield of all tillage treatments increased with an increase in fertilizer dosages (table 7).

Table 7. Tillage x fertilization effect on growth & yield parameters (Debrecen, 2018-2020)

Tillage treatments	Fertilizer treatments	Fertilizer Use Efficiency (FUE)	Agronomic Efficiency (AE)	Grain yield (t ha ⁻¹)	SPAD value	Plant Height (cm)	No. of leaves plant ⁻¹	Stem *circum (cm)	Cob * circum (cm)	Cob length (cm)	Rows cob ⁻¹	Kernels row ⁻¹
MT	N0	-	-	7.6	34.59	171.0	12.2	8.0	16.2	17.7	16.0	35.3
MT	N80	135.0	40.1	10.8	59.70	221.0	13.8	8.5	16.7	20.3	16.7	36.0
MT	N160	78.4	31.0	12.6	61.29	239.3	14.0	9.6	18.0	21.7	16.0	40.2
ST	N0	-	-	7.2	34.50	142.3	10.5	7.1	15.3	18.7	16.7	31.2
ST	N80	130.6	40.8	10.5	53.51	192.5	12.3	7.4	16.6	19.5	16.5	35.3
ST	N160	76.3	31.4	12.2	59.34	225.3	13.7	8.7	17.3	21.0	16.7	36.0
RT	N0	-	-	8.6	35.21	166.1	11.8	7.2	15.6	18.6	15.6	35.1
RT	N80	144.6	36.6	11.6	60.22	228.5	13.7	8.3	17.3	20.8	17.0	37.8
RT	N160	82.3	28.3	13.2	62.00	242.8	13.7	9.3	17.6	21.8	15.2	40.4
LSD _{0.05}				0.45	3.15	8.96	0.58	1.03	0.99	1.39	1.26	3.55
Fertilizer Use Efficiency (FUE) = Grain yield (kg)/N Fertilizer (kg) : Agronomic Efficiency (AE)=Yield of fertilized treatment- Yield of control (N0)/ N Fertilizer (kg) ; * circum=circumference												

Significantly higher fertilizer use efficiency (5.0-10.7%) was obtained with RT, compared to MT and ST (table 7), whereas, the Agronomic Efficiency (AE) of MT and ST ranged from 9.6% to 11.5% higher than RT. The higher FUE of RT suggests it was better able to utilize soil residual nutrient (N), while the higher AE of MT and ST indicate better utilization and greater yield increasing effect from applied fertilizer, compared to RT. The result also suggests risk of nitrate leaching is likely to be lower in RT due to its higher FUE. This suggestion is supported by findings of Daryanto et al. (2017) who reported increased nitrate leaching in minimum tillage compared to conventional tillage management and attributed it to the frequent occurrence of macropores (dead roots, earthworm burrows). However, Khan et al. (2017) & Issaka et al. (2019), found minimum tillage minimized the leaching of nutrients, especially nitrates, compared to conventional and deep tillage. According to Tao et al. (2018), to improve FUE and reduce leaching, field-specific N rates should be estimated using site factors such as rainfall, previous crop, tillage practice, soil drainage class, and N form and timing.

Tillage x fertilization interaction influenced growth and yield parameters to varying extent. There was no significant difference in leaf SPAD reading (VT growth stage) in the control (N0) of the three tillage practices, although the lowest reading (34.50) was recorded in ST. Leaf SPAD reading in ST x N160 and N80 was significantly lower than

MT and RT x N160 and N80. SPAD values closely correlated with the nitrogen dosage in all tillage treatment and was highest in N160, followed N80 and N0. Similar report by Yu et al. (2019), showed deep tillage increased the leaf SPAD value of high-yielding spring maize during the R1, R2, and R3 growth stages. Nagy (2010) and Széles (2007), also found that SPAD values increased with fertilization and there was a strong correlation between the SPAD values and irrigation.

The tallest plants (242.8 cm) were recorded in RT with N160 treatment, followed by MT x N160 (239.3 cm) and ST x N160 (225.3 cm). Differences in plant heights between ST and both MT and RT were statistically significant ($P < 0.05$). The number of leaves per plant was highest in MT x N160 but was not statistically significant compared to ST and RT. However, the number of leaves per plant was significantly lower in ST x N0 compared to MT and RT x N0. There was no significant difference in leaf area index (LAI) between RT and MT at N80. LAI was significantly higher in all tillage treatments with N160 compared to N80. The highest LAI was recorded in RT x N160, whereas the smallest LAI was in the control of ST tillage (fig. 33).

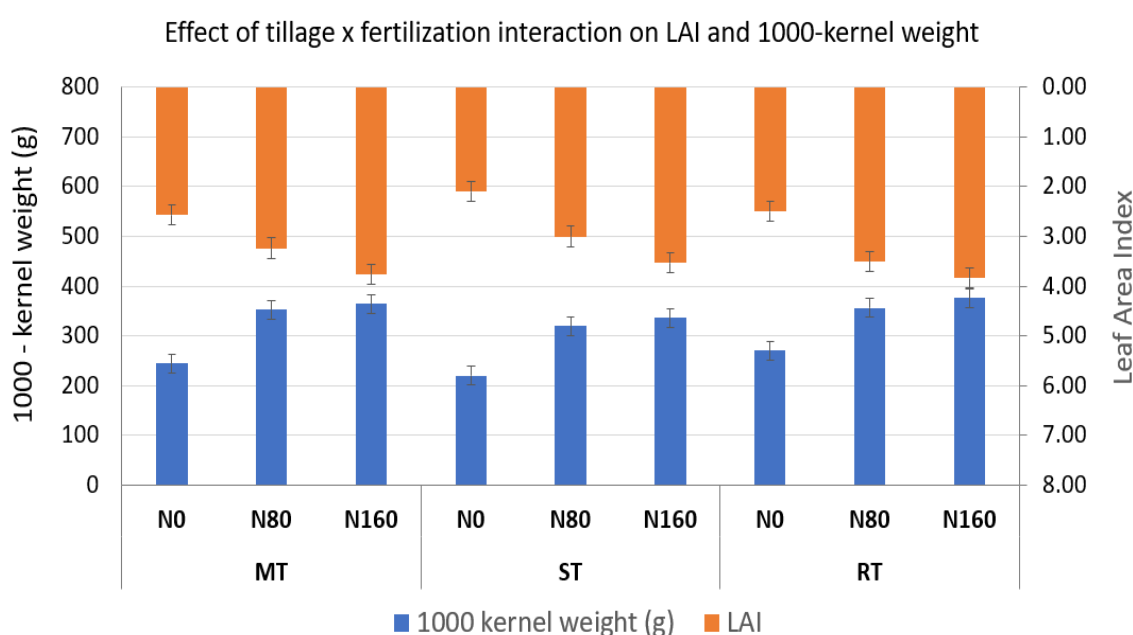


Figure 33. Tillage x fertilization interaction on LAI and 1000-kernel weight (Debrecen, 2018-2020)

Across all measured parameters, RT x fertilization interaction was most favorable. The results are consistent with report by Wasaya et al. (2017), who found tillage practices and N levels improved allometric traits, and grain yield and deep tillage produced the best results, compared to mouldboard and cultivator tillage systems. Earlier reports by

Wasaya et al. (2011), attributed increase in grain yield under deep ripping treatment to more grain weight per cob, as well as 1000-grain weight. Anjum et al. (2019) and Wang et al. (2015), also observed higher yields of maize in deep tillage system compared to mouldboard and minimum tillage systems and attributed the yield surplus to increased root length density, soil moisture content and nutrient uptake in the lower soil layer.

Fertilization significantly improved yield of all tillage treatments. The mean yield increase was 3.13 t ha⁻¹ with N80 and 4.84 t ha⁻¹ with N160 (Table 8).

Table 8. Yield and variance of tillage x fertilizer treatments (Debrecen, 2018-2020)

	Mean Yield (t ha ⁻¹)			Difference (b-a)	Difference (c-a)	Difference (c-b)
	N0 (a)	N80 (b)	N160 (c)			
MT	7.59 ^a	10.80 ^a	12.55 ^b	3.21	4.96	1.75
ST	7.19 ^a	10.45 ^a	12.21 ^a	3.26	5.02	1.76
RT	8.64 ^b	11.57 ^b	13.17 ^c	2.93	4.53	1.60
Mean	7.81	10.94	12.64	3.13	4.84	1.70
LSD _{0.05} = 0.45 Values with different letters in column differ significantly (P<0.05)						

The significantly higher yield of RT observed in the control-N0 (8.64 t ha⁻¹) demonstrated its superior ability to exploit natural soil nutrient reserve, compared to ST and MT. This observation is in harmony with reports by Wang et al. (2015), Al-Kaisi et al. (2015) and Schneider et al. (2017), who found that deep tillage (subsoiling) enhances root penetration and permit access to subsoil resources, hence higher yields, compared to conventional (MT) and minimum tillage (ST). Bramdeo & Rátonyi (2020), also found under condition of low nutrient supply (N0), RT yield significantly exceeded MT and ST. Wasaya et al. (2017), reported similar results, which showed different tillage practices and N levels significantly influence maize grain yield and harvest index. They reported that deep tillage together with a higher dose of nitrogen of 200 kg ha⁻¹ significantly increased dry matter content and grain yield of maize, compared to moldboard plowing and conventional tillage.

Among the three tillage treatments, ST was most responsive to increase level of fertilization with the highest incremental yield gain at both N80 (3.26 t ha⁻¹) and N160 (5.02 t ha⁻¹). However, differences in incremental yield gain among the three tillage practices were not statistically significant (P>0.05). Although RT yield was highest among all fertilizer treatments, the incremental yield gain from increase fertilizer dosage

was the lowest (table 8). Distinctly in the control, the significantly higher yield of RT demonstrated its ability to capture natural nutrient reserves in the soil.

In addition to improving yield in tillage treatments, fertilization also enhanced yield stability of the tillage systems. Yield variation was highest (CV=41%) in the control(N0) of tillage treatments and decreased significantly with N80 (20%) and further reduced to 12% with N160 treatments (fig. 34).

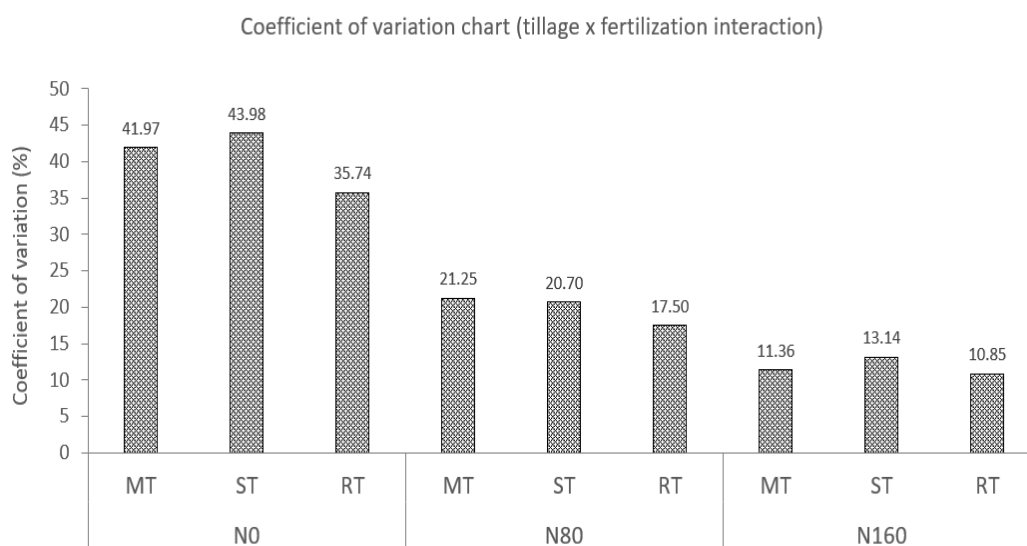


Figure 34. Coefficient of variation – tillage x fertilization interaction (Debrecen, 2018-2020)

Yield stability was highest in RT at all fertilization levels. Berzsényi & Dang (2006), reported similar findings, which showed that with increase fertilizer dosages, stability of maize yield improved but found no significant difference between N160 kg and N240 kg ha⁻¹ treatments. A higher yield gain from increase fertilizer dosages also suggests that fertilization can compensate to a limited extent for shortfall in tillage practices. Even though ST tillage yield was lowest in the control (table 8), with the addition of N80 yield significantly surpassed RT and MT in the control (N0). Györfy (1976), made similar observation and posited that the effects of tillage depth as well as the number of interventions are reduced or buffered for by fertilization. He noted that the impact of fertilization on yield and yield stability was significantly greater than that of tillage treatments. Likewise, Schneider et al. (2017), also found that topsoil fertilization cushioned both the extremely positive and negative effects of deep tillage. Buah et al. (2017), reported similar results, which showed no significant interaction between tillage practices and fertilizer treatments and concluded that maize response to fertilizer treatments was not affected by tillage systems.

4.2.9 Tillage x fertilization x year interaction

Although tillage, fertilization and year accounted for 3.5%, 39.9% and 1.1% of yield variance, respectively, interactions among these factors were not statistically significant (table 9).

Table 9. Test of significance, tillage x fertilization x year interaction (Debrecen, 2018-2020)

Dependent Variable: Yield

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	8356.066 ^a	26	321.387	59.879	0.000	0.448
Intercept	210898.960	1	210898.960	39293.747	0.000	0.953
Tillage	375.140	2	187.570	34.947	0.000	0.035
Fertilizer	7443.085	2	3721.543	693.381	0.000	0.420
Year	118.540	2	59.270	11.043	0.000	0.011
Tillage * Fertilizer	14.435	4	3.609	0.672	0.611	0.001
Tillage * Year	43.054	4	10.763	2.005	0.091	0.004
Fertilizer * Year	344.403	4	86.101	16.042	0.000	0.032
Tillage * Fertilizer * Year	17.408	8	2.176	0.405	0.918	0.002
Error	10288.999	1917	5.367			
Total	229544.025	1944				
Corrected Total	18645.065	1943				

a. R Squared = .448 (Adjusted R Squared = .441)

Bramdeo & Rátonyi (2020), however observed significant tillage x fertilization x year interaction in 2015-2016 crop-years. The difference in results could be attributed to the wide disparity in weather between the 2015 and 2016 crop-years, particularly the rainfall amount and distribution, compared to 2018- 2020. Similar findings by Nagy (2007), showed that fertilization was the decisive factor and the interaction between tillage and fertilization is modified under drought conditions.

Among the examined crop-years the highest-level interaction was observed in 2020, which was the most favorable crop-year (fig. 35). Yields of MT and ST in the control (N0) were severely affected by the high level of rainfall. RT yield was least affected and was most stable compared to ST and MT.

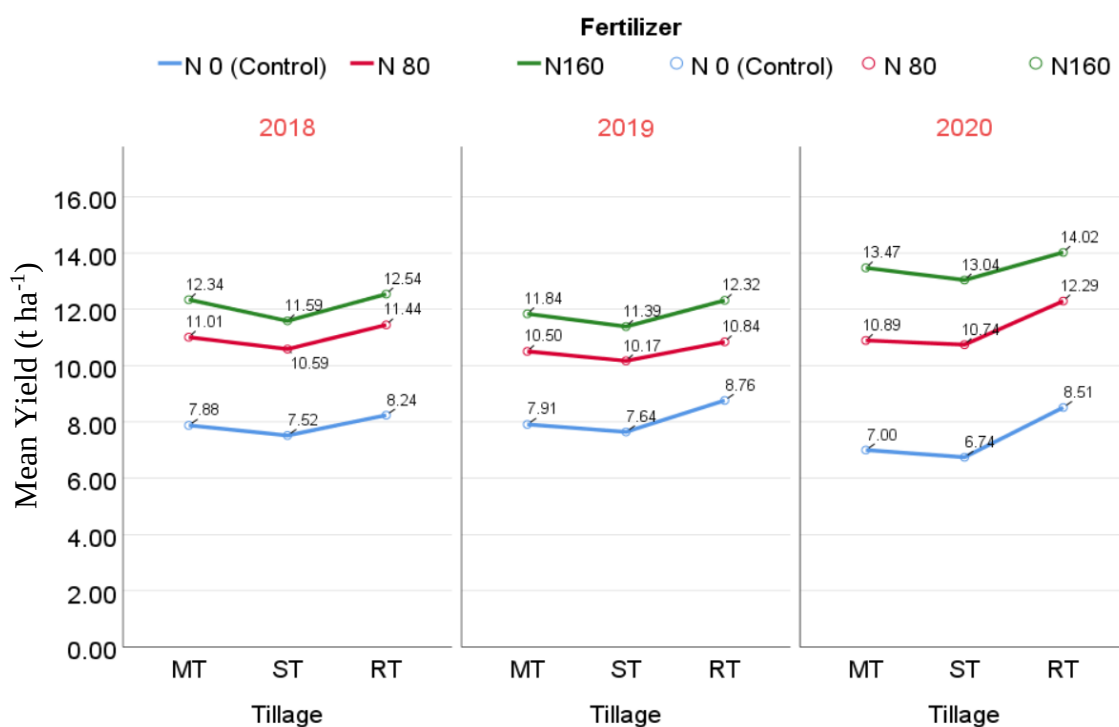


Figure 35. Tillage x year x fertilization interaction (Debrecen, 2018-2020)

The higher yield stability of RT in the control (N0) is in conformity with several research findings, which demonstrated the ability of deep tillage to exploit subsoil nutrient reserves, thereby buffering the imbalance of excess water-supply in the control (N0). Hence, yield was most affected in ST and MT because of the limited tillage depth and the high levels of water supply (rainfall) in 2020.

Similarly, Árendás et al. (2010), Berzsenyi et. al. (2011) and Orfanou et al. (2019), reported that the magnitude of the impact of agrotechnological inputs on yield are strongly modified by effect of the crop-year, as a result of variability in precipitation amount, distribution and temperature. Huynh et al. (2019), also reported that due to the difference in weather conditions, the effect of tillage was highly significant in some years, while in other years it was not.

4.3 Tillage x Irrigation Interaction

Tillage x irrigation interaction was not statistically significant ($P > 0.05$). Yield differences between irrigated and non-irrigated tillage treatments ranged from -0.26 to 0.01 t ha⁻¹ (table 10).

Table 10. Yield of tillage treatments in irrigated and non-irrigated plots (Debrecen, 2018-2020)

		Mean Yield (t ha ⁻¹)- (2018-2020)		Difference (b-a)	Percentage (%)
		Non-irrigated (a)	Irrigated (b)		
Tillage	MT	10.30 ^a	10.33 ^a	0.03	0.29
	ST	10.06 ^a	9.80 ^b	-0.26	-2.58
	RT	10.99 ^b	11.00 ^c	0.01	0.09
	Mean	10.45	10.38	-0.07	-0.70
	LSD _{0.05} =0.34 Values with different letters in column differ significantly (P<0.05)				

The marginal variance between irrigated and non-irrigated treatments suggests that the crop water demand was favorably met with GSR during the examined period (both in amount and distribution). The good water holding capacity of the chernozem soil at the experimental site also augmented soil moisture availability.

In year with low rainfall and under moisture deficit condition, irrigation was found to have greater effect on yield compared to favourable crop-year with adequate water supply (Bramdeo & Rátonyi, 2020; Nagy, 2007; Dóka & Pepó, 2009). Similarly, Huynh et al. (2019), found that irrigation significantly increased yields of sandy soil in dry conditions and was the most essential, compared to tillage and crop rotation. Likewise, in Bangladesh, Rahman et al. (2015), reported maize yield was more dependent on irrigation practices, rather than tillage systems.

Water supply of the crop-year significantly influenced soil moisture content. The need for irrigation is therefore highly dependent on the water supply of the crop year. In 2018 and 2019, there was marginal yield increases from irrigation, which suggests that the available soil moisture was close to the needs of the plant and there was no significant moisture deficit.

In 2020, there was no yield increasing benefit from irrigation, instead yield depression occurred in all tillage treatments (fig. 36). Strip tillage (ST) was most affected (-0.94 t ha⁻¹) followed by MT (-0.45 t ha⁻¹) and RT (-0.44 t ha⁻¹). The negative impact of irrigation on grain yield is tantamount to over-irrigation and supports several research findings, that there exists, a positive correlation between nutrient supply and irrigation and both must be simultaneously synchronized for optimum results (Fanus et al., 2014; Jamil, 2004; Nagy, 2007).

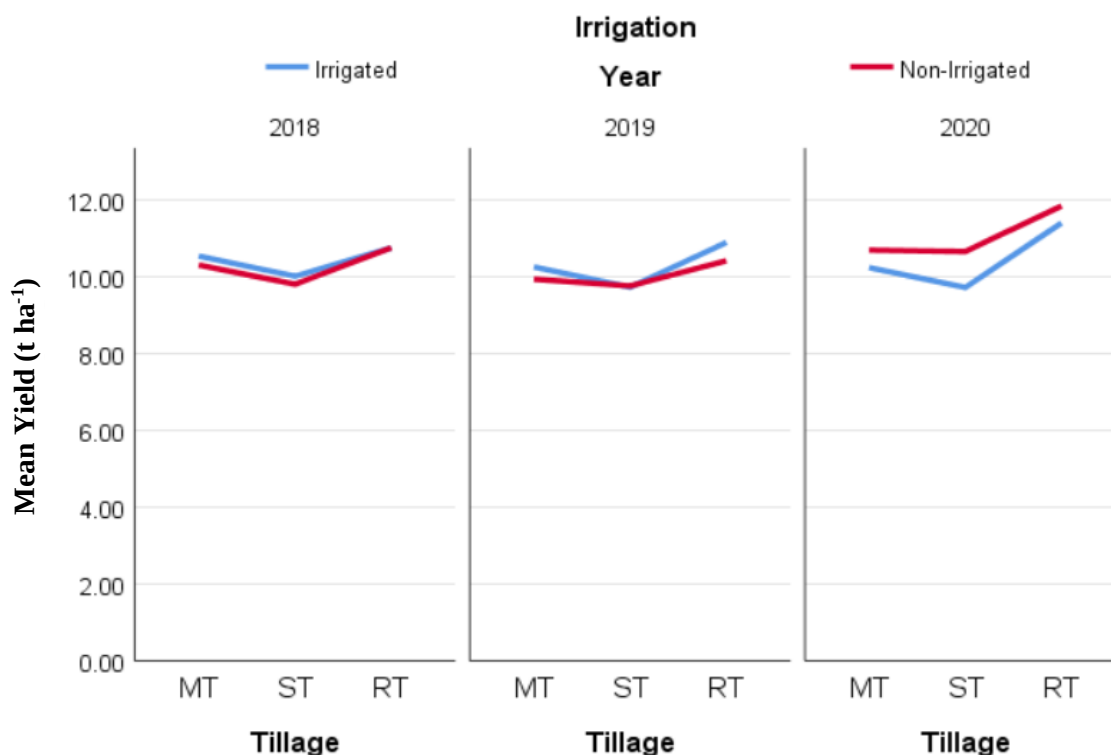


Figure 36. Tillage x irrigation x year interaction (Debrecen, 2018-2020)

The highest yield decline in the ST plots (-0.94) due to irrigation in 2020 is also consistent with earlier report by Bramdeo & Rátonyi (2020), who observed ST was most affected by irrigation in the control plots (N0) compared to RT and MT. Strip tillage soil moisture content was always found to be higher than MT and RT (Ferencsik & Rátonyi, 2014; Bramdeo & Rátonyi, 2020) and therefore demand for irrigation would be less, compared to MT and RT. The reduction in irrigation water requirement for ST is corroborated with reports by Lamm et al. (2009), who found that at the minimum irrigation capacity, strip tillage recorded the highest incremental grain yield, compared to conventional and non-till. Roger et al. (2007), also found that due to higher soil moisture, yield of strip-tilled corn was superior to corn grown with conventional tillage.

The adverse effect of irrigation on yield in 2020, highlighted the need for harmonization of the agrotechnological inputs and suggests that RT and MT are more suited for favorable crop-years, compared to ST, which has been reported by several researchers to be more adaptable for drought conditions.

4.3.1 Tillage x planting density interaction

Tillage x planting density interaction was not statistically significant (table 11).

Table 11. Tests of significance: tillage x planting density interaction

Tests of Between-Subjects Effects						
Dependent Variable: Yield						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	5369.188 ^a	8	671.148	97.822	0.000	0.288
Intercept	210898.960	1	210898.960	30739.173	0.000	0.941
Tillage	375.140	2	187.570	27.339	0.000	0.027
Plant density	4950.256	2	2475.128	360.758	0.000	0.272
Tillage * Plant density	43.791	4	10.948	1.596	0.173	0.003
Error	13275.877	1935	6.861			
Total	229544.025	1944				
Corrected Total	18645.065	1943				

a. R Squared = .288 (Adjusted R Squared = .285)

Within group interaction was statistically significant ($P < 0.05$). RT yield was significantly higher than MT and ST at 60,000 and 80,000 plants ha^{-1} in monoculture (fig. 37).

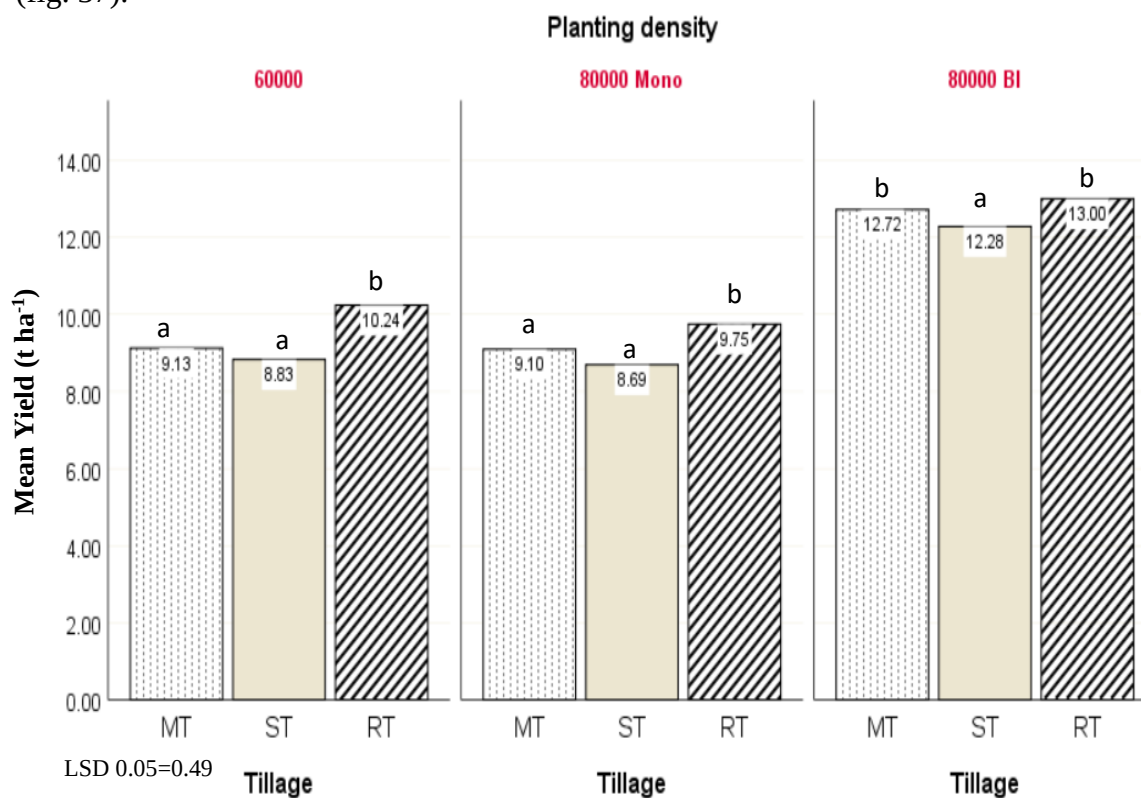


Figure 37. Yield of maize in tillage x planting density interaction (Debrecen, 2018-2020)

At 80,000 plants ha⁻¹ in biculture (Bi), yield significantly increased for all tillage treatments, with yield of RT exceeding MT and ST by 2 and 6% respectively. Yield difference between MT and RT at 80,000 plants ha⁻¹ (Bi) was not statistically significant. Yield increment from 60,000 (mono) to 80,000 (biculture) was highest in MT 3.59 t ha⁻¹, followed by ST 3.45 and RT 2.76 t ha⁻¹ (MT>ST>RT). The results demonstrated that RT potential to sustain higher plant population density is significantly greater than MT and ST in monoculture cropping systems (low nutrient supply). Bramdeo & Rátonyi (2020), made similar observations, which showed MT was most responsive to biculture treatments, while RT was best suited for monoculture maize. The increase in yield and smaller yield differential among tillage practices at 80,000 Bi also demonstrated the potential of soil fertility (biculture) to compensate for shortcoming in tillage practices.

It is also very evident that the yield performance of tillage systems was more influenced by soil fertility (biculture), rather than planting density. The potential of RT to sustain higher plant population was also observed by Yu et al. (2019), who reported a significant interaction between tillage practices and planting density. They found that increasing maize plant density from 75,000 plants ha⁻¹ to 90,000 plants ha⁻¹, increased yield in both rotary and subsoil tillage yields. However, when the planting densities were increase more than 90,000 plants ha⁻¹, the yields stopped increasing in rotary tillage, whereas, subsoil tillage facilitated an additional increase in density of 15,000 plants ha⁻¹ and improve yield to 1.08 - 1.94 t ha⁻¹. Wang et al. (2016), also demonstrated that with high planting densities, subsoiling fostered the accumulation of root dry matter during the early stages of maize growth and improved the absorption capacity of the roots for water and nutrients, leading to higher yields. In contrasting report, Lamm et al. (2009), after evaluating three planting densities, found yields of maize at 74,500 and 82,300 plants ha⁻¹ were greater for the strip and no tillage systems, while the maximum yield under conventional tillage was achieved at the lowest density of 66,300 plant ha⁻¹. They attributed the lower yield at the higher density in conventional tillage to increased plant water stress, which resulted in earlier plant senescence when plant density was too high for the available plant water supply. Based on the results of this research and finding by Lamm et al. (2009), it is evident that the level of interaction between tillage practices x planting density is influenced by soil fertility as well and water supply (moisture content of the soil) and under condition of limited water supply, ST can sustain a higher plant population compared to moldboard tillage.

4.3.2 Crop-year x tillage x planting density interaction

Crop-year x tillage x planting density interaction was statistically significant (table 12).

Table 12. Test of significance: crop-year x tillage x planting density interaction

Tests of Between-Subjects Effects						
Dependent Variable: Yield						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	6067.048 ^a	26	233.348	35.564	0.000	0.325
Intercept	210898.960	1	210898.960	32142.849	0.000	0.944
Tillage	375.140	2	187.570	28.587	0.000	0.029
Plant density	4950.256	2	2475.128	377.231	0.000	0.282
Year	118.540	2	59.270	9.033	0.000	0.009
Tillage * Plant density	43.791	4	10.948	1.669	0.155	0.003
Tillage * Year	43.054	4	10.763	1.640	0.161	0.003
Plant density * Year	389.910	4	97.478	14.856	0.000	0.030
Tillage * Plant density * Year	146.356	8	18.294	2.788	0.005	0.012
Error	12578.017	1917	6.561			
Total	229544.025	1944				
Corrected Total	18645.065	1943				

a. R Squared = .325 (Adjusted R Squared = .316)

Yield differences between 60 and 80,000 plants ha⁻¹ (mono) in ST and MT was not significant in any examined years. However, RT yield was significantly lower at 80,000 plants ha⁻¹(mono) compared to 60,000 plants ha⁻¹ in 2018 and 2020 (fig. 38).

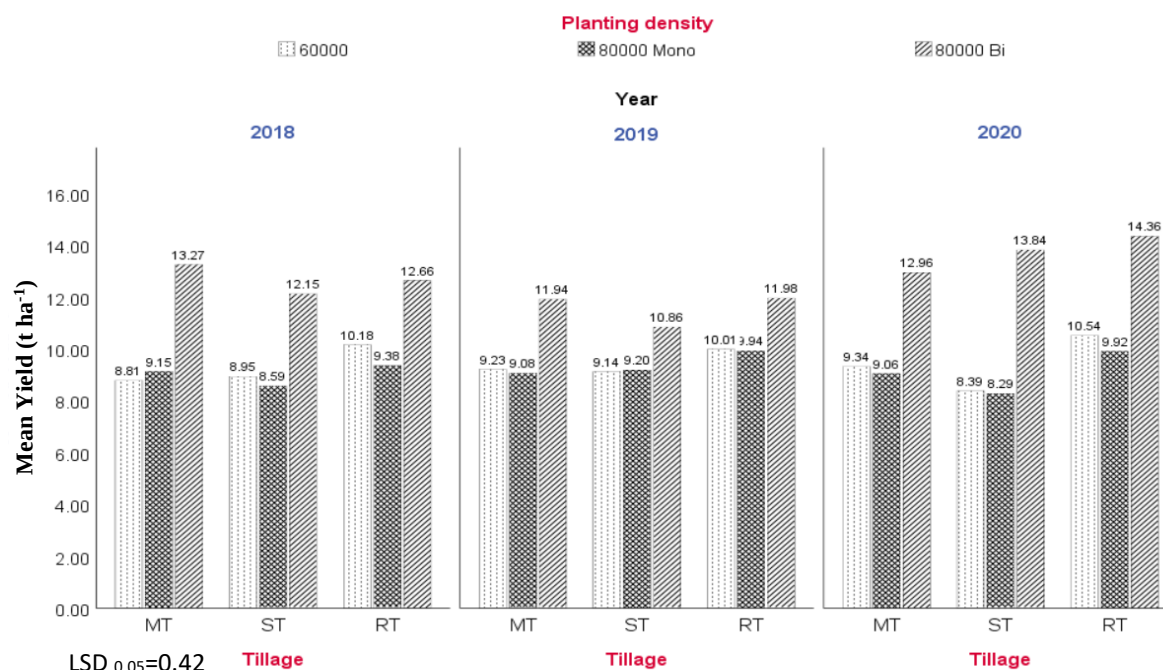


Figure 38. Crop-year x tillage x planting density interaction (Debrecen, 2018-2020)

In 2019, which recorded the least GSR, there was no significant difference between the two plant densities (mono). The significant difference in yield of RT between the two planting densities in 2018 & 2020 demonstrated that RT yield best at lower planting density in favorable and wet years, while in drier year (2019) its potential to sustain higher density is improved. The highest yield increment from tillage x planting density interaction occurred in all tillage treatments x 80,000 plants ha⁻¹ (Bi) in all the examined years but was more pronounced in MT, and in 2020 with the highest GSR. The significantly higher yield gain from 80,000 plants ha⁻¹ (Bi) compared to 60 and 80,000 (mono) also demonstrated the importance of synchronizing soil fertility (biculture) and water supply (2020) with increase in plant density, for optimum yield gain. Bramdeo & Rátonyi (2020), made a similar observation and concluded MT was more suitable for intensive cropping system after observing that yield increment from increase planting density was highest with MT compared to ST and RT. In similar research Baghdadi et al. (2012), found that the effect of tillage, plant density and their interaction on maize growth rate was significant at high planting density (130,000 plants ha⁻¹) and a more intensive tillage system was better for corn when planted at high density, compared to corn planted at lower densities (60,000 plants ha⁻¹).

4.3.3 Tillage x hybrids interaction

Tillage x hybrid interaction was not significant ($P>0.05$). However, RT was most favored by all the hybrids and yield differences were significant, compared to ST and MT (table 13).

Table 13. Tillage x hybrid interaction (Debrecen, 2018-2020)

		Mean yield (t ha ⁻¹) - (2018-2020)		
		Armagnac (FAO 490)	Loupiac (FAO 380)	Fornad (FAO 420)
Tillage	MT	10.49 ^a	10.12 ^a	10.33 ^a
	ST	10.12 ^a	9.70 ^a	9.98 ^a
	RT	10.84 ^b	11.24 ^b	10.91 ^b
	Mean	10.48	10.35	10.41
	LSD _{0.05} = 0.43 Values with different letters in column differ significantly ($P<0.05$)			

Among the test hybrids, Loupiac (FAO 380) yield was highest in RT (11.24 t ha⁻¹), while Armagnac (FAO 490) yield was superior in both MT and ST.

Although mean yield differences between MT and ST for the test hybrids over the examined period (2018-2020) were not statistically significant, differences in the respective crop-year were significant.

Shinoto et al. (2019), also observed that interactions between hybrid and tillage were not significant. They evaluated the performance of six maize genotypes on rotary tillage and chisel plowing and found that although there were significant differences in the early stages of growth, the differences were not significant in other stages. Gwenzi et al. (2008), however, found that tillage x genotype interactions had significant ($p < 0.05$) impact on maize grain yield. Their results showed that in semi-arid region, yield of maize genotypes were significantly higher in tillage system with higher moisture concentration (ridge/furrow), compared to flat bed systems.

4.3.4 Tillage x hybrid x year interaction

The largest yield differential among the hybrids was observed in 2020 (fig. 39), which recorded the highest GSR and underscore the influence of weather on performance of genotypes.

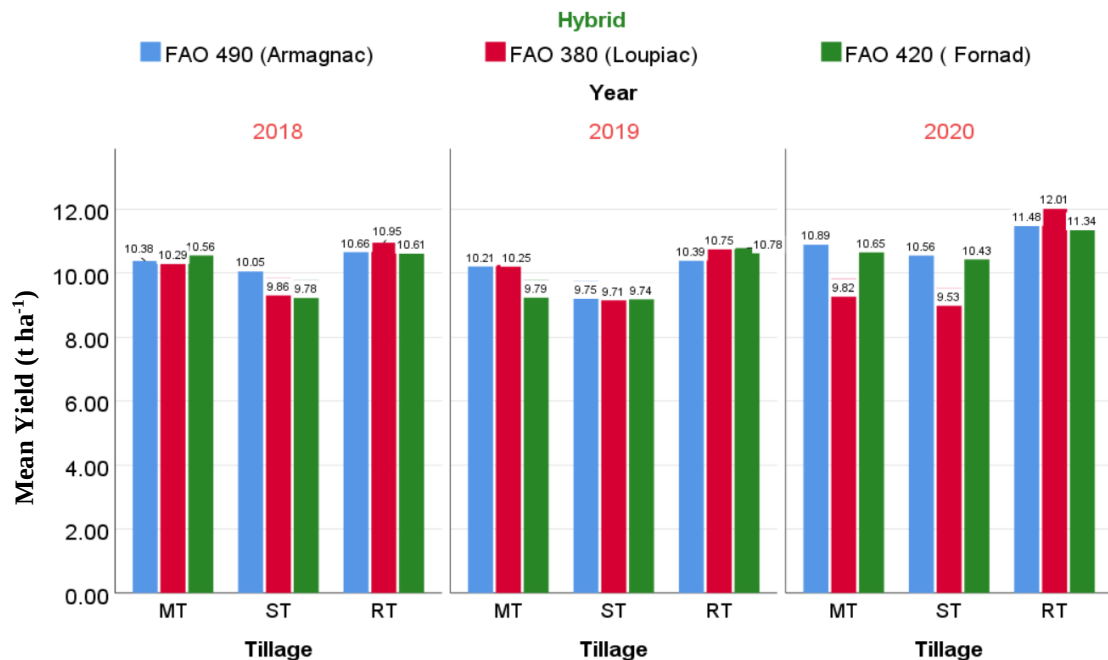


Figure 39. tillage x hybrid x year interaction ((Debrecen, 2018-2020)

The yield of all three hybrids was most stable in RT in all the examined years. Fornad yield was significantly lower than Loupiac and Armagnac in MT x 2019, whereas in MT x 2018, there was no significant difference in yield. This observation suggests that

Fornad is less adaptable to year with low growing season rainfall (2019) and MT tillage, which also recorded the lowest moisture of the three tillage systems. In 2020, both Armagnac and Fornad yield was significantly higher than Loupiac in MT and ST, while there was no significant difference in RT. The result is corroborated by report of Széles et al. (2019a) who found longer maturing hybrid had greater efficiency in utilization of precipitation and fertilization compared to short maturity hybrid. The result also suggests that RT can help to cushion to some extent, the shortfall in hybrid's adaptability to variation in environmental conditions (weather), hence the most stable yield in RT for the test hybrids in all three years, compared to MT and ST.

4.3.5 Interaction of tillage x irrig. x fert. x forecrop on yield increment.

Tillage x irrigation x forecrop x fertilization interaction was statistically significant ($P < 0.05$). Tillage treatments in monoculture plots were adversely affected by irrigation, particularly the N0 and N80 in 2018 (fig. 40a) and 2019 (fig. 40b), whereas, in 2020

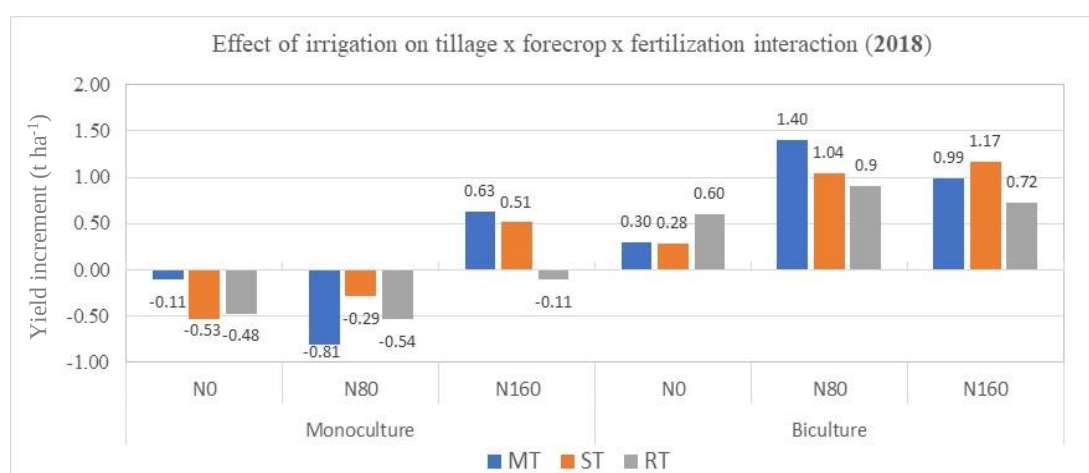


Figure 40a. Effect of irrigation on tillage x forecrop x fertilization interaction (Debrecen, 2018)

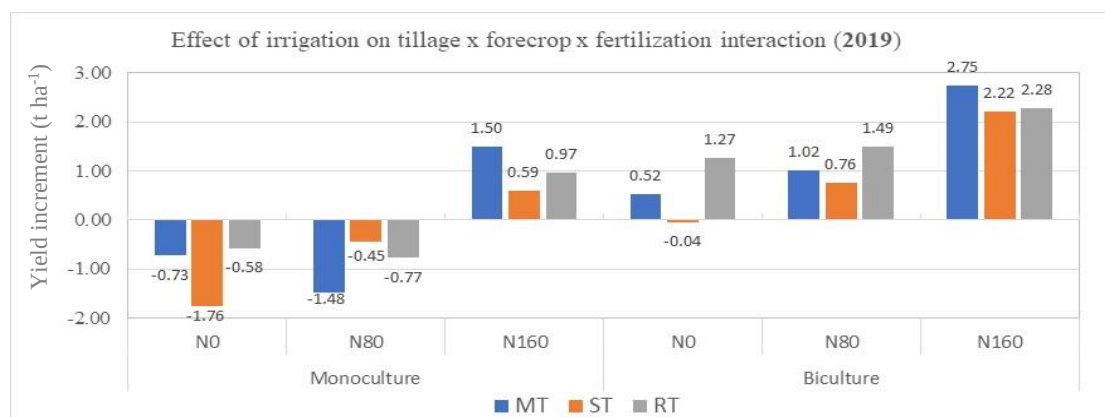


Figure 40b. Effect of irrigation on tillage x forecrop x fertilization interaction (Debrecen, 2019)

yield decline was most severe in all monoculture treatments (fig. 40c).

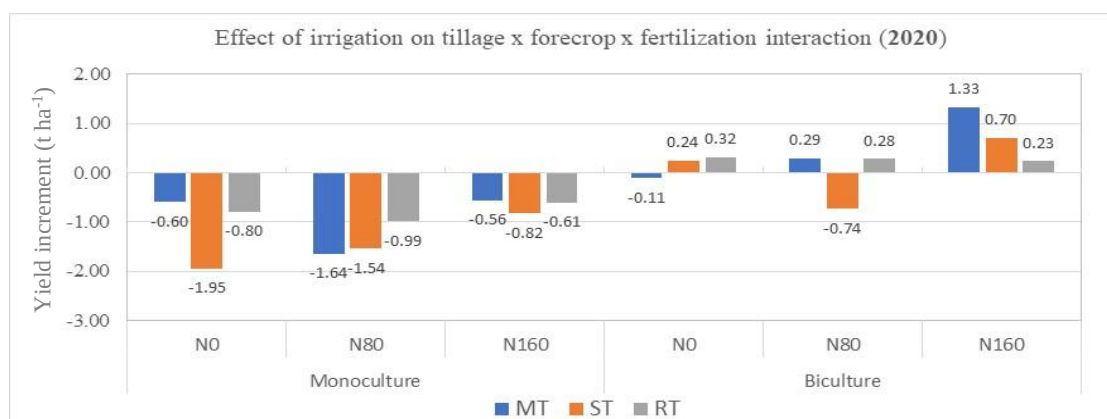


Figure 40c. Effect of irrigation on tillage x forecrop x fertilization interaction (Debrecen, 2020)

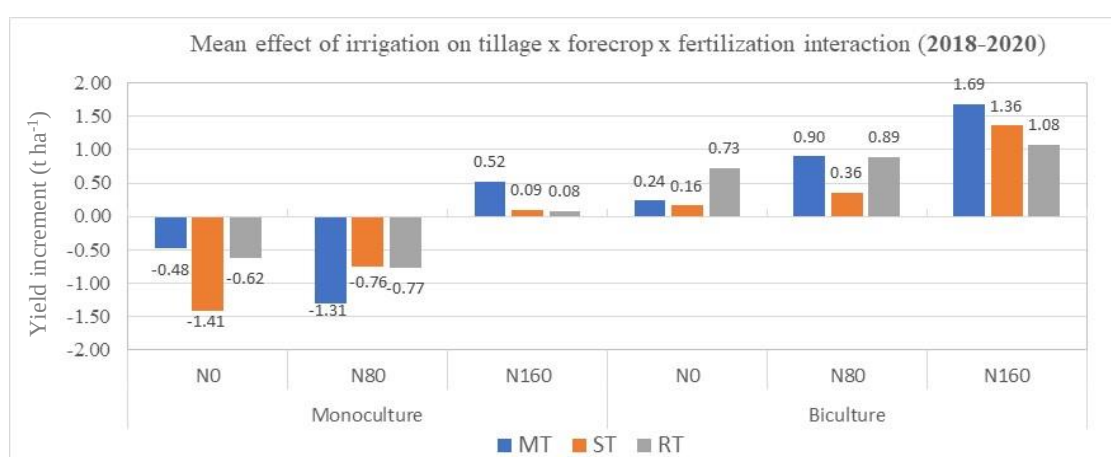


Figure 40d. Irrigation x tillage x forecrop x fertilization interaction (Debrecen, 2018-2020)

Yield increment from irrigation x tillage x fertilization x forecrop interaction was highest in 2019 (fig. 40b), which recorded the least growing season rainfall, whereas the lowest yield increment was observed in 2020 with the highest GSR. ST was most affected by irrigation in the control (N0) and could be attributed to the higher moisture level due to its conservative nature, compared to RT and MT. The results demonstrated that crop production factors do not act independently but interacts with each other and the level of interaction is modified by the prevailing weather condition of the crop-year.

In 2020, GSR significantly exceeded 2018 and 2019, hence, irrigation would have resulted in surplus of soil moisture for which the nutrient supply was inadequate. Yield increment from irrigation of all tillage x fertilization x biculture treatments was generally positive, except for an anomaly in 2020 where ST biculture + N80 was affected by irrigation. The negative impact of irrigation in biculture x tillage x fertilization treatments was also observed by Bramdeo & Rátonyi (2020), in 2016 which recorded

similar GSR as 2020 (452 vs. 433 mm). The anomaly in 2020 could therefore be attributed to the year effect, due to the high levels of GSR rainfall and would require further investigation.

Generally, MT showed the highest fertilizer use efficiency and responded best to irrigation and higher fertilizer dosage (N160) with a yield increment of 1.69 t ha⁻¹ in biculture and 0.52 t ha⁻¹ in monoculture (fig. 40d). The result suggests that MT is more suitable for favorable crop-years (high rainfall) and intensive maize production, as opposed to RT and ST. Mean yield decline due to irrigation in monoculture tillage plots with N80 and N0 treatments ranged from 0.48 to 1.41 t ha⁻¹. Benefits of irrigation was realized only at N160 in monoculture and with all fertilization levels in biculture. The positive effect of irrigation on fertilization x tillage interaction in biculture cropping system and the negative effect in N0 and N80 in monoculture is in harmony with research findings that biculture system enhanced soil fertility and simultaneous adjustment of both irrigation and fertilization is necessary for optimum results (Megyes et al., 2005; Csajbók et al., 2014). The result is also consistent with research findings that agronomic management factors do not act independently but interacts and optimum yield can only be achieved with proper selection of the appropriate levels of these factors.

4.4 Effect of crop rotation on yield

Maize germination and growth were observed to be more uniform in biculture treatment plots, compared to monoculture. The distinct variation in growth between the control (N0) and N80 in monoculture was absent in biculture, thus reflecting the higher soil fertility of the latter. Mean yield of maize with winter wheat forecrop was 36.4% (3.38 t ha⁻¹) higher than monoculture (table 14).

Table 14. Maize yield: monoculture vs. biculture cropping systems (Debrecen, 2018-2020)

Year	Mean Yield (t ha ⁻¹)		Difference (b-a)	Percentage (%)
	Monoculture (a)	Biculture (b)		
2018	9.18 ^a	12.69 ^a	3.51	38.24
2019	9.43 ^a	11.59 ^b	2.16	22.91
2020	9.26 ^a	13.72 ^c	4.46	48.16
Mean	9.29	12.67	3.38	36.44
LSD _{0.05} =0.29 Values with different letters in column differ significantly				

In addition to increasing yield, crop rotation also enhanced yield stability through reduction of yield variation. The highest yield gain from winter wheat forecrop was 4.46 t ha⁻¹ (48.16%) in the most favorable crop-year (2020), while the smallest gain (2.16 t ha⁻¹) was in 2019, which recorded the least GSR. The benefits derived from crop rotation in improving yield stability are reflected in a reduction in the coefficient of variation from 32% in monoculture to 13% in biculture (fig. 41).

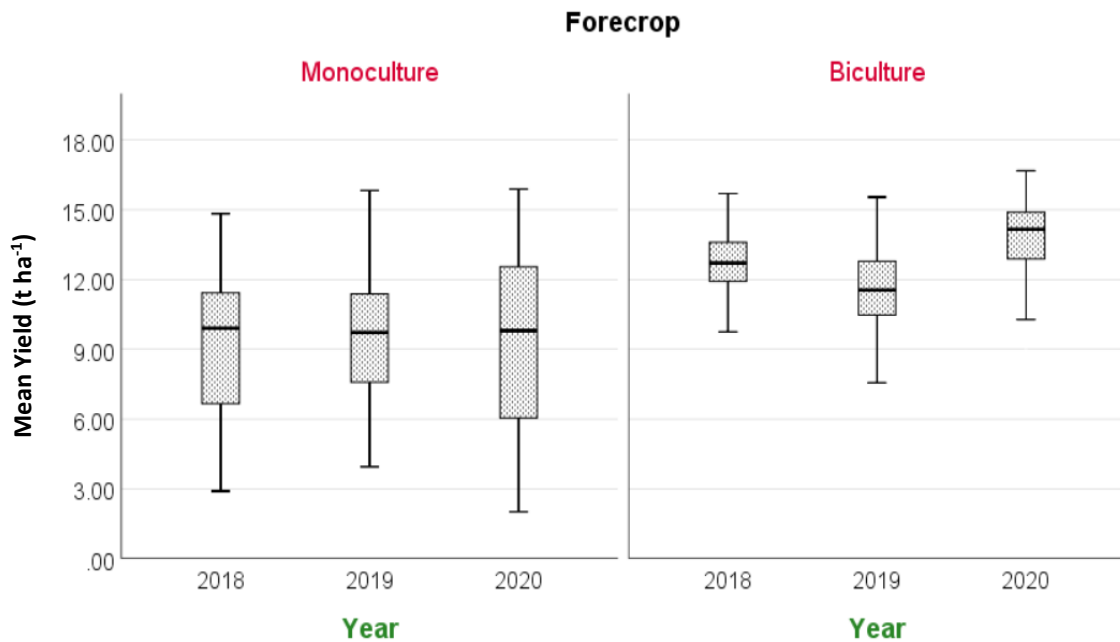


Figure 41. Boxplot yield of monoculture vs. biculture by crop year (Debrecen, 2018-2020)

The results demonstrated that winter wheat forecrop (crop rotation) incorporated as part of the maize production system can improve yield by 3.36 t ha⁻¹ (2.16 to 4.46 t ha⁻¹) and reduced yield variation. Significant yield variation in cropping system among the examined years also highlighted the influence of the weather and the superiority of biculture cropping system to stabilize yield under varying climatic conditions.

Several researchers have reported similar findings. Dan TerAvest of Washington State University, USA, reported that crop rotation had significant impact on yield of maize with yield increment ranging from 11 to 58% higher than monoculture maize. According to Below (2018), soybeans forecrop can increase corn yield by 25-bushel (635 kg) and if corn was the previous crop, there will be a 25-bushel (635 kg) penalty. Uzoh et al. (2019), reported maize in velvet bean-maize rotation increased maize yield by over 100% and posited that the degree of the rotation benefit is influenced by both the type

of forecrop and climatic condition. According to Roth (1996), maize cultivated after soybeans forecrop, can be grown with 40 lbs ac⁻¹ less nitrogen fertilizer. Sárvári & Pepó (2014), reported that maize cultivated in rotation with winter wheat forecrop recorded higher yield (+1.58 t ha⁻¹) compared to monoculture maize. Similar report by Bramdeo & Rátonyi (2020a), showed maize cultivated in rotation with winter wheat forecrop, yield 28% (2.47 tons) higher than monoculture maize. Evaluating the effect of crop rotation over a nine-year period, Huynh et al. (2019), also found that crop rotation significantly increased and maintained maize yield under both plowed and irrigated conditions with an average increase of 1.1 t ha⁻¹ per year.

4.4.1 Forecrop x fertilization interaction

Crop rotation x fertilization interaction was statistically significant ($P < 0.05$). The greatest benefit of crop rotation was observed in the control (N0) with a yield increment of 5.73 t ha⁻¹ (table 15). The result demonstrated that winter wheat forecrop significantly enhanced soil fertility and can buffer for a reduction in applied fertilizer dosage, which can also help in minimizing the risks associated with nitrate leaching.

Table 15. Mean yield- fertilizer x forecrop interaction (Debrecen, 2018-2020)

Fertilizer treatments	Mean yield (t ha ⁻¹)		Difference (b-a)	Percentage (%)
	Monoculture (a)	Biculture (b)		
N0	5.89 ^a	11.62 ^a	5.73	97.28
N80	9.83 ^b	13.17 ^b	3.34	33.98
N160	12.15 ^c	13.22 ^b	1.07	8.81
LSD _{0.05} = 0.47 Values with different letters in column differ significantly ($P < 0.05$)				

Fertilizer use efficiency (FUE) was significantly reduced with higher fertilizer dosages in both cropping systems, from 33.98% with N80 to 8.81% in N160 but was more pronounced in biculture cropping system.

There was no significant difference in yield between N80 and N160 in biculture cropping system (13.17 vs. 13.22 t ha⁻¹), whereas in monoculture there was a 24% (2.32 t ha⁻¹) yield increase. The higher FUE in monoculture, suggests a lower soil nutrient status compared to biculture and therefore fertilizer demand is higher. Although continuous

maize cropping system is considered less environmentally friendly, its higher FUE is likely to reduce chances of N-pollution.

Yield surplus from forecrop x fertilization interaction varied with crop-year and was highest in the most favorable crop-year (2020), whereas the lowest yield increment was in 2019, which recorded the least GSR during the examined period (fig. 42).

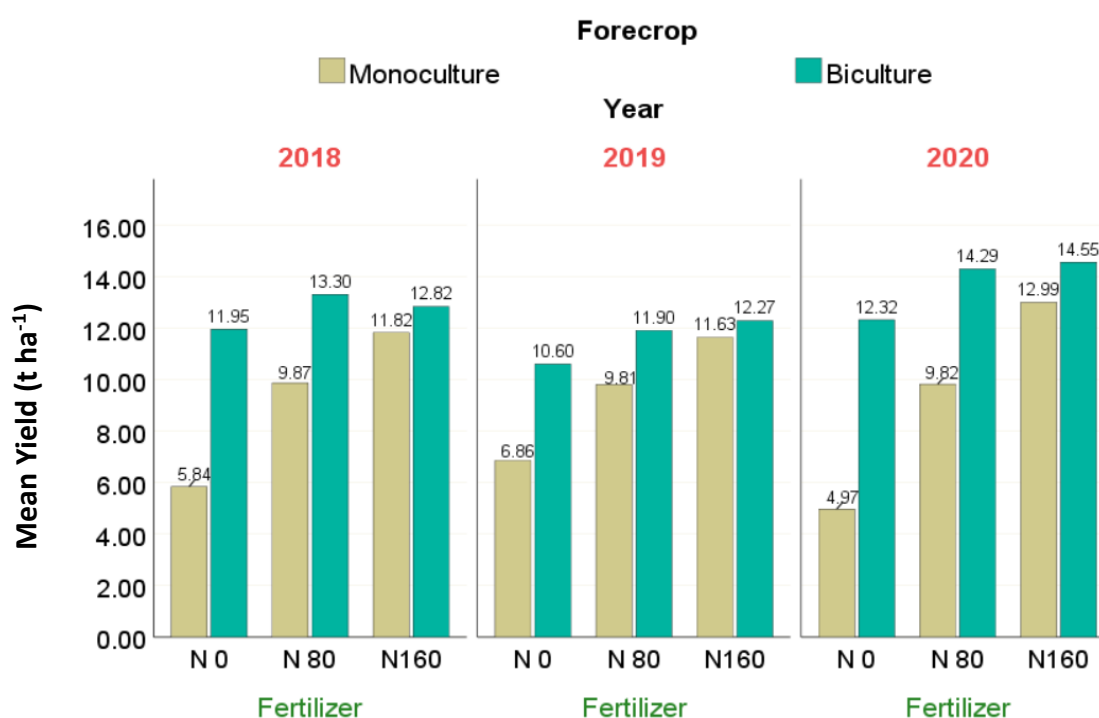


Figure 42. Fertilization x forecrop x year interaction (Debrecen, 2018-2020)

The result suggests that optimum fertilizer dosage is dependent on both water supply of the crop-year (precipitation), as well as the cropping system (forecrop), and is consistent with findings of Pepó et al. (2008). The smaller yield increment from higher fertilizer dosages in biculture, significantly reduced the Nitrogen use efficiency (NUE) and agrees with report by Sárvári (1995), that maize cultivated in rotation with winter wheat forecrop (biculture) can save on applied fertilizer of 40 kg ha⁻¹ less (60-80 kg ha⁻¹) compared to monoculture (100-120 kg N ha⁻¹) and this value was even lower in triculture rotation. Ma et al. (2003), also stated that maize cultivated in rotation with legume crops could enhanced maize yields by about 20% and lower the quantity of applied N fertilizer by almost 180 kg ha⁻¹. Similar report by Bramdeo & Rátonyi (2020), revealed that biculture maize (winter wheat forecrop) on chernozem soil can save on applied fertilizer dosage of at least 50 kg N ha⁻¹. The use of crop rotation in maize production system can therefore reduce on the amount of N fertilizer applied and minimize the possible risk of

nitrate leaching into the environment, by improving availability of soil nitrogen (Al-Kaisi M. & Kwaw-Mensah, 2018).

4.4.2 Forecrop x Irrigation Interaction

Forecrop x irrigation interaction was statistically significant ($P < 0.05$). Maize yield in irrigated biculture plots benefitted from irrigation, while monoculture yields were adversely affected by irrigation (table 16).

Table 16. Yield of maize forecrop x irrigation interaction (Debrecen, 2018-2020)

	Mean Yield (t ha ⁻¹)		Difference (b-a)	Percentage (%)
	Non-irrigated (a)	Irrigated (b)		
Monoculture	9.57 ^a	9.03 ^a	-0.54	-5.64
Biculture	12.26 ^b	13.08 ^b	0.82	6.69
LSD _{0.05} = 0.35 Values with different letters in column differ significantly				

The effect of irrigation on maize yield in the two cropping system was highly influenced by water supply of the crop year. Irrigation of biculture maize enhanced yield in all the examined years, while in monoculture yield was negatively affected. The highest yield gain from biculture irrigation was observed in the year with the lowest GSR (2019 = +1.36

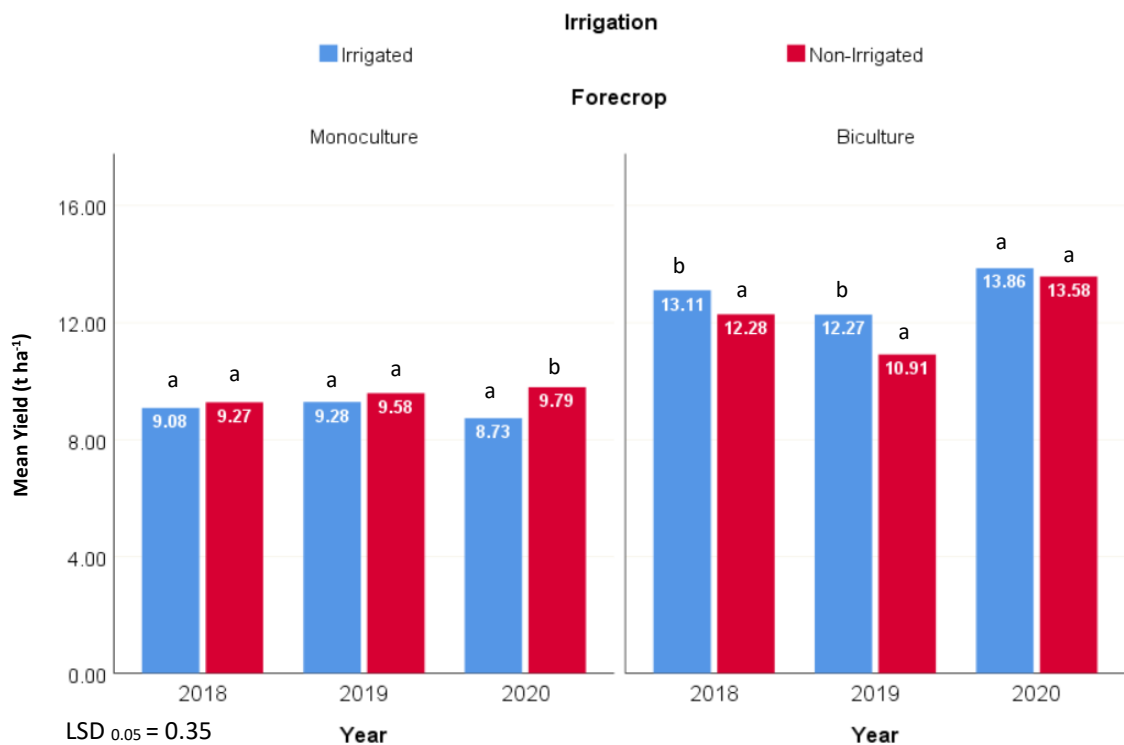


Figure 43. Interaction of year x irrigation x forecrop on yield (Debrecen, 2018-2020)

t ha⁻¹), while marginal yield gain was obtained in 2020 (0.22 t ha⁻¹) with the highest GSR. Yield decline of monoculture irrigation was significant ($P < 0.05$) in 2020, compared to 2018 and 2019 (fig.43).

The yield surplus from irrigation in biculture and negative impact in monoculture is supported by research findings, which demonstrated a positive correlation between soil nutrient and water supply. Soil with higher nutrient status (biculture) will benefit from higher levels of irrigation, compared to low nutrient soil (monoculture) and therefore the harmonization of water supply with soil fertility is fundamental for optimum results (Nagy 1995, 2007, Megyes et al., 2005; Csajbók et al., 2014). Similar findings by Pepó et al. (2008), demonstrated that water supply (rainfall) and irrigation on yield of maize was strongly modified by crop rotation and yield-surpluses was lower in monoculture, compared to bi and triculture. They observed in extremely dry year (2007), yield increment from irrigation was highest in monoculture compared to bi and triculture maize. The result is also supported by work of Huynh et al. (2019), who reported that the interactive effects of crop rotation with either tillage or irrigation on yield of maize is dependent mainly on the weather condition of the crop-year and is highly significant under extreme water deficit condition.

4.4.3 Crop rotation x hybrid interaction

Forecrop x hybrid interaction was statistically significant ($P < 0.05$). Yield of all the test hybrids significantly increased under biculture cropping system. Armagnac (FAO 420) responded most favorably to biculture cropping system with 47.51% yield increase (table 17), compared to Fornad (31.18%) and Loupiac (30.78%).

Table 17. Yield of hybrid x forecrop interaction (Debrecen, 2018-2020)

Hybrids	Mean yield (t ha ⁻¹)		Difference (b-a)	Percentage (%)
	Monoculture (a)	Biculture (b)		
Armagnac (FAO 490)	9.05 ^a	13.35 ^a	4.30	47.51
Loupiac (FAO 380)	9.39 ^a	12.28 ^b	2.89	30.78
Fornad (FAO 420)	9.43 ^a	12.37 ^b	2.94	31.18
LSD 0.05= 0.43 Values with different letters in column differ significantly ($P < 0.05$)				

Yield differences among hybrids in monoculture cropping were not significant in 2018 and 2020 (fig. 44), whereas, in 2019 yield of Armagnac (FAO 490) was significantly lower than Loupiac (FAO 380) and Fornad (FAO 420).

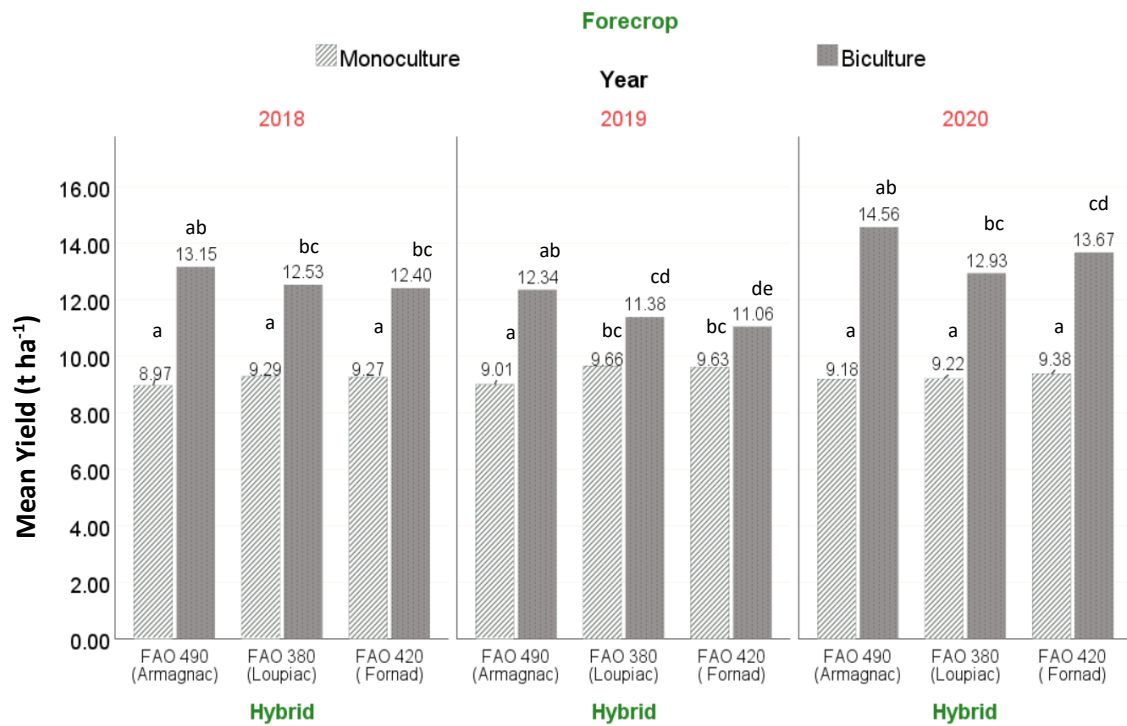


Figure 44. Hybrid x forecrop x year interaction (Debrecen, 2018-2020)

The results revealed Armagnac (FAO 490) was most affected by the low precipitation of 2019, coupled with the higher density (80,000 plants ha⁻¹) and low nutrient supply of monoculture. This observation is consistent with findings of Magari et al. (1997) and Hallauer & Russell (1961), who found various hybrids displayed different levels of stability pertaining to environmental effect and genotype belonging to a later maturity grouping are more susceptible to unfavorable environmental conditions. According to Berzsenyi & Dang (2006), as the vegetation period of hybrids lengthens the stable plant density range narrowed and shifted towards lower plant densities of 50-70,000 plants ha⁻¹ versus 50-90,000 plants ha⁻¹. Széles et al. (2019), also reported similar performance for the three test hybrids during the 2016-2017 crop-years, which showed Armagnac (FAO 490) yield in the control (N0) was the lowest (6.47 t ha⁻¹), whereas yield of Loupiac (FAO 490) and Fornad (FAO 420) was significantly higher with no significant difference (7.02 vs. 6.90 t ha⁻¹) between the two. The significantly higher yield of Armagnac (FAO 490) in biculture during the examined period is also consistent with findings of Magari et al. (1997) and Mousavi et al. (2017).

4.5 Effect of fertilization on maize yield

Fertilization accounted for the largest yield variance (40%) among the agrotechnological inputs and significantly influenced growth, yield parameters and nutritional content of maize. The lack of nitrogen in the control (N0), manifested in deficiency symptoms (fig.45), shortest plant, smallest LAI, lowest SPAD reading, reduced number of leaves, lowest 1000-kernel weight and ultimately the lowest grain yield (table 18).

Table 18. Growth and yield parameters of fertilization treatments (Debrecen, 2018-2020)

	Mean yield (t ha ⁻¹)	SPAD Value	Plant height (cm)	No. of leaves per plant	Cob length (cm)	1000 kernel weight (g)	LAI
N0	7.80 ^a	34.77 ^a	159.7 ^a	11.5 ^a	18.3 ^a	232.2 ^a	2.5 ^a
N80	10.94 ^b	57.81 ^b	214.0 ^b	13.3 ^b	20.2 ^b	348.5 ^b	3.3 ^b
N160	12.50 ^c	60.87 ^b	235.7 ^c	13.8 ^c	21.5 ^c	365.1 ^c	3.7 ^c
		LSD _{0.05}	values with different letters in column differ significantly				

N160 treatment delivered the best results for growth and yield parameters and was significantly higher than N80, except for the SPAD value (VT growth stage).

In similar research Šarčević-Todosijević et al. (2018), found nitrogen fertilization had a significant impact on maize yield and observed increasing the rate of applied nitrogen up to 120 kg ha⁻¹, increased plant height, total leaves, length of a cob, grain rows and the total grains per cob, after which all the measured parameters declined with higher rate (N180 kg).

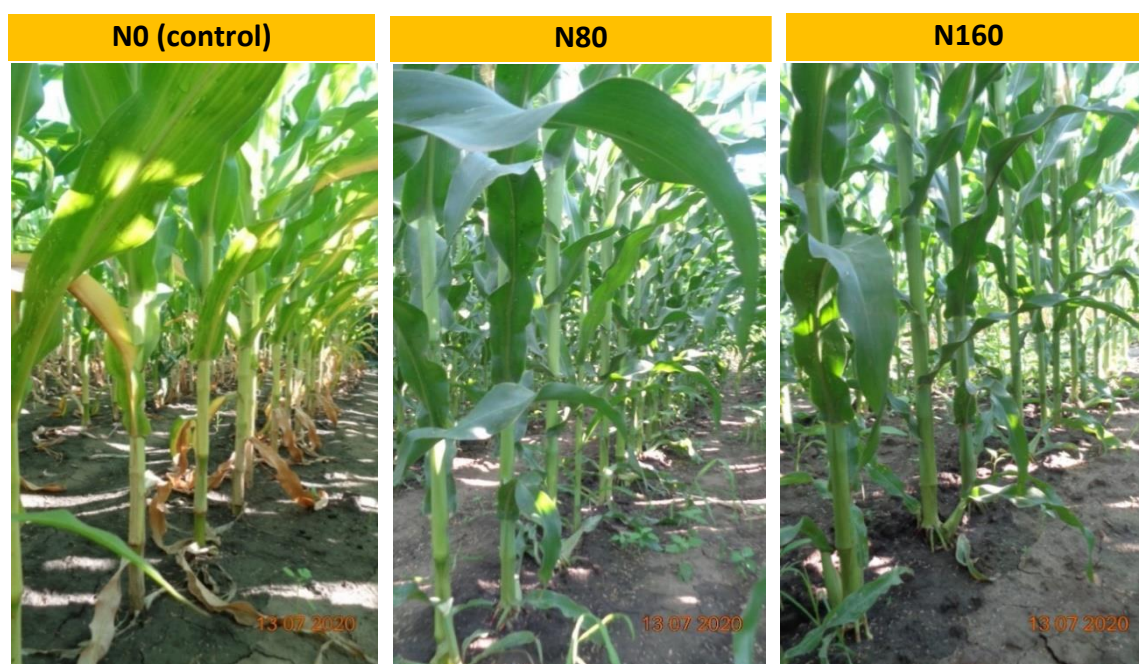


Figure 45. Maize plant in control (N0), N80 and N160 fertilization treatments (Debrecen, 2020)

4.5.1 Fertilization x year interaction

Yield differences between treatments were statistically significant in all years (table 19).

Table 19. Yield of fertilization x year interaction (Debrecen, 2018-2020)

		Mean Yield (t ha ⁻¹)		
		2018	2019	2020
Fertilizer treatments	N0	7.88 ^a	8.11 ^a	7.42 ^a
	N80	11.01 ^b	10.50 ^b	11.31 ^b
	N160	12.16 ^c	11.85 ^c	13.51 ^c
		LSD _{0.05} = 0.45 Values with different letters in column differ significantly		

Yield increment from N80, ranged from 29-52%, with a mean of 40%, while N160 ranged 46-82% with a mean of 61%. The highest yield gain from fertilization was in 2020. Yield increment from fertilization closely correlated growing season rainfall. Bramdeo & Rátonyi (2020), reported similar results, which showed in the favorable crop-year (2016), with adequate growing season rainfall yield increase from fertilization was 40%. They also observed no yield increasing effect from N160 in 2015, which was a relatively dry crop-year. The results also concurred with findings by Pepó (2007), that under favorable weather conditions, fertilization could improve yield up to 50%, and in drought years, it has no yield increasing effect.

Agronomic Nitrogen use efficiency (ANUE) was lowest in 2019, which recorded the least growing season rainfall (GSR), whereas the highest ANUE was observed in 2020 with the highest GSR (442.3 mm).

Under condition of low GSR (2019) the WUE increased, whereas the NUE decreased (table 20), while in year with adequate rainfall (2020) the WUE is reduced and the NUE improved, resulting in higher yield.

Table 20: Agronomic nitrogen and water use efficiency(rainfall) by crop year (Debrecen, 2018-2020)

			2018	2019	2020
Growing Season Rainfall (GSR) (mm)			317.9	290.2	442.3
Agronomic N efficiency (AEN) kg grain per kg N	N80		39.1	29.9	48.6
	N160		26.8	23.4	38.1
Water use efficiency (WUE)		N0	25.0	28.8	17.6
kg grain per mm GSR		N80	34.6	36.6	26.6
		N160	37.4	38.3	30.8

Csajbók et al. (2014), reported similar findings which showed that water use efficiency of maize was higher under dry conditions. The result is also in harmony with reports by Nagy (2007), Karancsi (2013) and Széles et al. (2018), who found that fertilization improves water use efficiency of maize hybrids.

Mean NUE decreased with increased fertilizer dosage. NUE at N80 level was superior (+25%) to N160 in all the examined years. The lowest NUE coincides with the year with the least rainfall. Similar observation was made by Pepó & Karancsi (2017), who found increasing fertilizer dosages from N90 to N150 kg ha⁻¹ significantly reduce the nitrogen use efficiency, especially in year with low rainfall (2013), compared to year with adequate precipitation (2014). The decrease in incremental yield gain from increasing fertilizer dosages is also in conformity with the law of diminishing returns and supported by findings of Nagy (2003) and Pepó & Karancsi (2014), who observed yield increment from fertilization was the highest at lower dosages, while at higher dosages it was more modest.

Fertilization x crop-year interaction was statistically significant ($P < 0.05$). For the same treatment level, yield varied significantly among the examined crop-years. The effect of fertilization x crop-year interaction on the yield of maize has been widely reported and is often observed in long-term experiments (Orfanou et al., 2019; Buah et al., 2017; Pepó & Csajbók, 2013). Weather is known to regulate heat and water supply of the plant environment and therefore influences material transformation, nutrient uptake and ultimately crop growth and development (Kovács, 1982; Nagy, 1996).

To test the correlation between growing season rainfall and maize yield with the different fertilization treatments during the examined period, data were utilized from the experimental site over a six-year period (2015-2020) to generate more meaningful scatter plots (fig. 46).

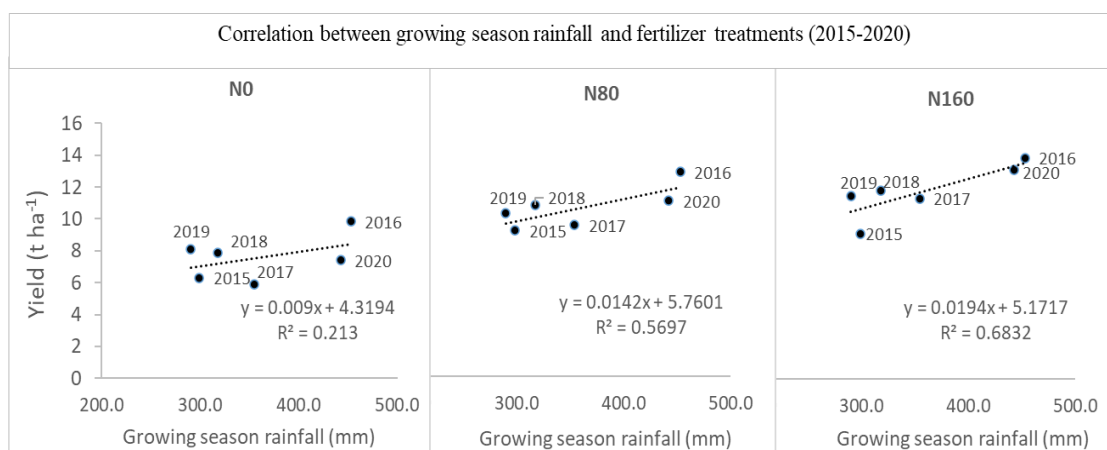


Figure 46. Correlation between fertilizer treatments and rainfall (Debrecen, 2015-2020)

The results showed a positive correlation existed between growing season rainfall and the yield of maize in the all fertilization treatments (fig. 46). The strength of the correlation, however, varied with the level of fertilization. The strongest correlation between growing season rainfall and fertilization treatment was observed at N160 level ($r=0.83$), followed by N80 ($r=0.75$), while the control (N0) showed moderate correlation ($r=0.46$). This observation is in conformity with results of long-term experiments which showed a strong correlation between the nutrient and water supply of maize and higher water use efficiency (WUE) with increasement of nutrient supply (Pepó & Karancsi, 2014; Széles et al., 2018).

Fertilization impact on yield was significant and the effect size was modified by the weather condition of the specific crop-year, particularly the precipitation which showed an increasingly strong and positive correlation with higher fertilizer dosages. The result is corroborated by findings of Šarčević-Todosijević et al. (2018), Bocz & Nagy (1981), Nagy (2003), Vári (2013), Berzsenyi & Dang (2006), Pepó & Csajbók (2013), Széles et al. (2018) and Bramdeo & Rátonyi (2020).

Based on the results, N80 is the better option than N160 due to its higher NUE, which make it more economically and environmentally sustainable. The results confirmed that effect of agrotechnical inputs on yield of maize are modified by the weather condition of the prevailing crop-year. Therefore, with adequate water supply, higher dosages of fertilizer can improve yield surplus, while under condition of limited water supply, optimum yield can be achieved at lower dosages. This conclusion concurred with report by Wiswakumar et al. (2008) and Pepó & Csajbók (2013) that the harmful effect of weather condition can be mitigated with prudent nutrient and water management.

4.5.2 Fertilization x irrigation interaction

Fertilization x irrigation interaction was statistically significant ($P < 0.05$). Irrigation impacted negatively on yield in the control (N0) of all the examined years (fig.47). Yield

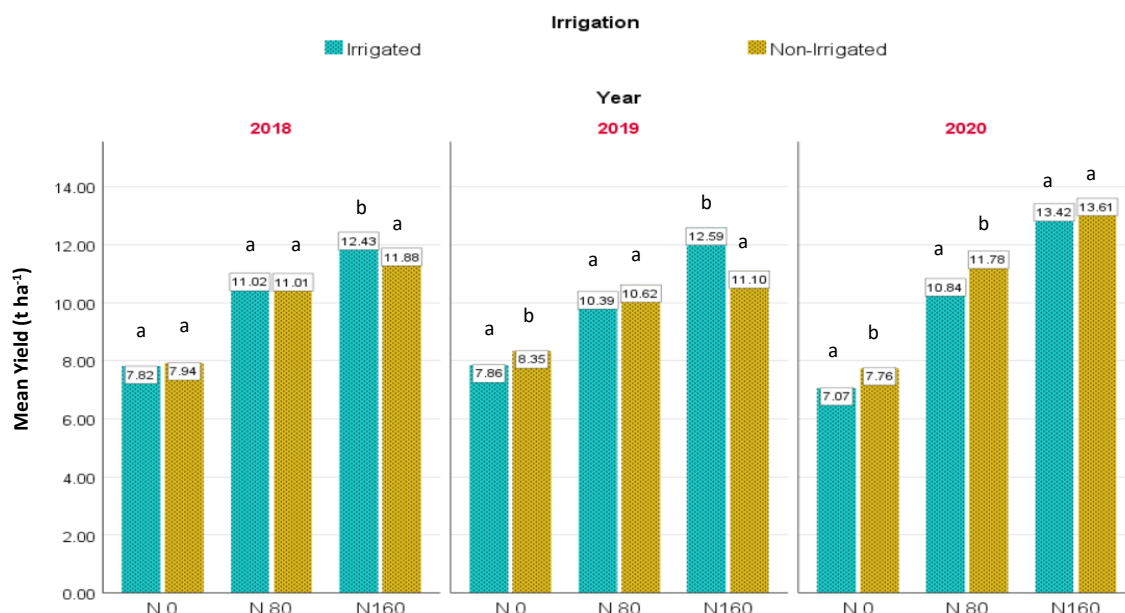


Figure 47. Fertilization x irrigation x year interaction (Debrecen, 2018-2020)

decline in the control ranged from 1.5% (0.12 t ha⁻¹) in 2018, 6% (0.50 t ha⁻¹) in 2019, to a high of 8.9% (0.69 t ha⁻¹) in 2020. Yield decline from irrigation was also evident at N80 level in 2019 (-0.23 t ha⁻¹) and 2020 (-0.94 t ha⁻¹), whereas in 2018 the yield of irrigated and non-irrigated was on par.

At N160 level yield gain from irrigation was highest in 2019 (1.49 t ha⁻¹), followed by 2018 (0.55 t ha⁻¹), whereas, a marginal decline was observed in 2020 (-0.19 t ha⁻¹). This observation concurred with that of Pepó & Karancsi (2014) and Meges (2005), who found that irrigation (water supply) and fertilization had significant effect on maize yield and yield surplus from irrigation and fertilization varied significantly with crop-year. The finding also agrees with report by Bocz & Nagy (1981) and Nagy (1994), that water supply and fertilization are not independent of each other but interact and mutually enhance the benefits of each other. They posited that the effect of fertilization is enhanced as water supply to the crop is increased to optimum level and thereafter, decreased when the water supply far exceeds the demand. The negative impact of irrigation, particularly in the control (N0) is also consistent with observation made by Bramdeo & Rátonyi (2020), Huzsvai & Széles (2009), Salazar et al. (2012) and is in conformity with findings of Nagy (2007) who posited that the yield increasing effect of

water supply on fertilization could be attributed to the positive relationship between the two factors

The results demonstrated that the effect of irrigation is dependent on the nutrient level of the soil, which is influenced by the applied fertilizer dosages, as well as the weather condition of the crop-year, particularly the rainfall amount and distribution. In year with relatively low rainfall, yield increment from irrigation was greater (2019), while in year with high rainfall (2020) the yield increasing effect was compromised. The result also confirmed that the chernozem soil at the experimental has good water holding capacity, which is capable of sustaining growth with N80 fertilization without the need for irrigation.

4.5.3 Fertilization x planting density interaction

Fertilization x planting density interaction was highly significant ($P < 0.01$). Yield of 60,000 plants ha^{-1} in the control (N0) of monoculture plots was 13% (0.8 t ha^{-1}) higher than 80,000 plants ha^{-1} , while in biculture plots with a standard 80,000 density, yield was 6.13 and 5.33 t ha^{-1} higher than 60 and 80,000 in monoculture, respectively (table 21).

Table 21. Plant densities yield and individual plant productivity (Debrecen, 2018-2020)

	Mean yield (t ha^{-1})			Mean yield (g plant^{-1})		
	N0	N80	N160	N0	N80	N160
60,000 plants ha^{-1} (Mono)- a	6.29	10.00	11.92	105	167	199
80,000 plants ha^{-1} (Mono) -b	5.49	9.67	12.38	69	121	155
80,000 plants ha^{-1} (Biculture)-c	11.62	13.17	13.22	145	165	165
Difference (b-a)	-0.80	-0.33	0.47	-36	-46	-44
Difference (c-b)	6.13	3.50	0.84	76	44	10
Difference (c-a)	5.33	3.17	1.30	40	-2	-34

The yield differential between the two planting densities in monoculture plot was reduced from 13% (0.80 t ha^{-1}) in the control (N0) to 3% (0.33 t ha^{-1}) with N80, and at N160 the difference was neutralized and yield surpassed the lower density by 4% (0.47 t ha^{-1}). The results demonstrated that the lower yield (-2.3%) with 80,000 plants ha^{-1} under monoculture cropping system was due to exhaustion of soil nutrient and cannot be sustained with less than N160 kg ha^{-1} . The increased in yield with N160 + 80,000

plants (mono), also improves the fertilizer use efficiency (FUE) compared to N160 + 60,000 plants ha⁻¹.

The increase in yield of 80,000 plant (mono) + N160 was concomitant with a decrease in individual plant productivity from 199 g to 155 g (table 21), whereas at 80,000 plants+N160 in biculture the individual plant productivity was 165 g. Based on the foregoing observations, the optimum plant density on chernozem soil with N80 x monoculture cropping system lies between 60 to 80,000 plants ha⁻¹, since there was a yield penalty at the higher density.

A plant density of 70,000 plants ha⁻¹ was most ideal for chernozem soil, in comparison to 80,000 which recorded 3% lower yield and 90,000 plants ha⁻¹ with 8% reduction (Nagy & Pepó, 2015; Pepó and Murányi 2014). Increasing plant density, increases the yield per unit area until the optimum density is reached, beyond which yield declines. The increase in yield from higher plant population is accompanied by a reduction in individual plant productivity (Sárvári 2005). The improvement in nitrogen use efficiency with N160 at the higher density, is corroborated by report of Nagy & Pepó, (2015), that the proper plant number can only be use with the consideration of other factors which are responsible for forming the yield. The need to be guided by NUE in determining optimum plating density is also supported by work of Xu et al. (2017), who found reducing nitrogen fertilizer dosages from 360 kg ha⁻¹ to 180 kg ha⁻¹ and increasing the planting density from 67,500 plants ha⁻¹ to 90,000 plants ha⁻¹ did not significantly changed the yield and improved the NUE.

4.5.4 Fertilization x plant density x year interaction

Fertilization x plant density x year interaction was significant ($P < 0.05$). Yield of the 80,000 plants ha⁻¹ (mono) in the control (N0) was the lowest (4.55 t ha⁻¹) in 2020 (fig.

48), which was the most favorable crop-year. In the same year, however, yield of 80,000 plants ha^{-1} + N0 (biculture) was 12.32 t ha^{-1} .

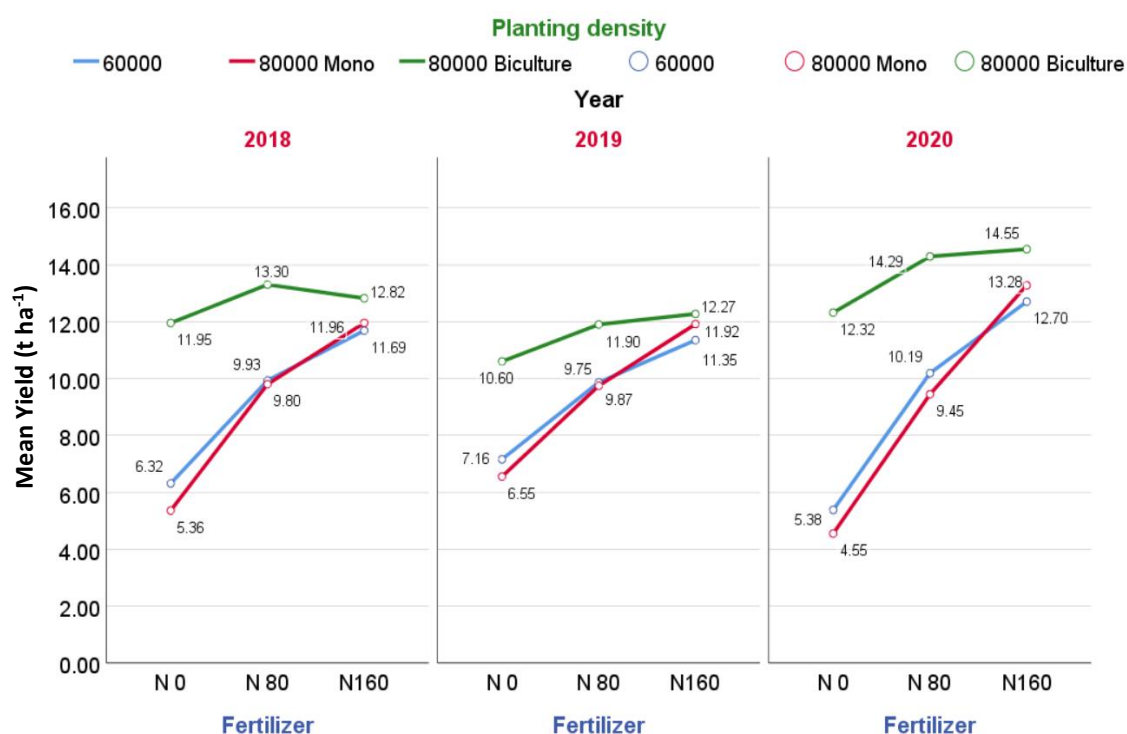


Figure 48. Crop year fertilization x plant density interaction (Debrecen, 2018-2020)

It was evident that the high fertility of soil in the control (N0) of biculture plots responded positively to the abundance of rainfall in 2020, while the same level of rainfall adversely affected yield in the control (N0) of the monoculture plots owing to the lower nutrient status.

Yield fluctuation was higher in the control at both planting densities and was significantly reduced with N80 treatment. This observation concurred with earlier findings that improvement in soil fertility can reduce fluctuation and enhance yield stability. Yield increment from N80 and N160 treatment was smallest in 2019, which recorded the least growing season rainfall. In 2018, N160 did not had any yield increasing effect on 80,000 plant ha^{-1} (biculture). Similar observation was made by Bramdeo & Rátonyi (2020), Pepó et al. (2008) and Berzsenyi et al. (2011).

The results demonstrated that in crop-year with good water supply (rainfall), crop productivity can be enhanced with higher levels of inputs (plant population & fertilizer).

4.5.5 Fertilizer x hybrid x year interaction

Fertilization significantly increased the yield of all the hybrids. Mean yield in the control (N0) was 7.80 t ha⁻¹, with no significant difference in yield among the three hybrids. Yield increase with N80 amounted to 40% (+3.14 t ha⁻¹), while N160 improved yield by 60% (+5.33 t ha⁻¹). At N160 level, Armagnac (FAO 490) lead over Loupiac (FAO 380) and Fornad (FAO 420) was marginal with a 0.38 t ha⁻¹ (3%) above the mean (table 22) but the difference was not significant.

Table 22. Hybrid yield x fertilization treatments (Debrecen, 2018-2020)

Dependent Variable: Yield

Fertilizer	Hybrid	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
N 0	FAO 490 (Armagnac)	7.794	0.164	7.474	8.115
	FAO 380 (Loupiac)	7.727	0.164	7.406	8.048
	FAO 420 (Fornad)	7.878	0.164	7.557	8.198
N 80	FAO 490 (Armagnac)	10.926	0.164	10.606	11.247
	FAO 380 (Loupiac)	10.950	0.164	10.629	11.271
	FAO 420 (Fornad)	10.951	0.164	10.631	11.272
N160	FAO 490 (Armagnac)	12.737	0.164	12.416	13.057
	FAO 380 (Loupiac)	12.379	0.164	12.058	12.700
	FAO 420 (Fornad)	12.399	0.164	12.078	12.720

Except for the influence of 2020 crop-year on hybrid x N160 treatment, differences in yield of the test hybrids was not statistically significant ($P>0.05$) in any of the fertilization treatment during the examined period (figure 49).

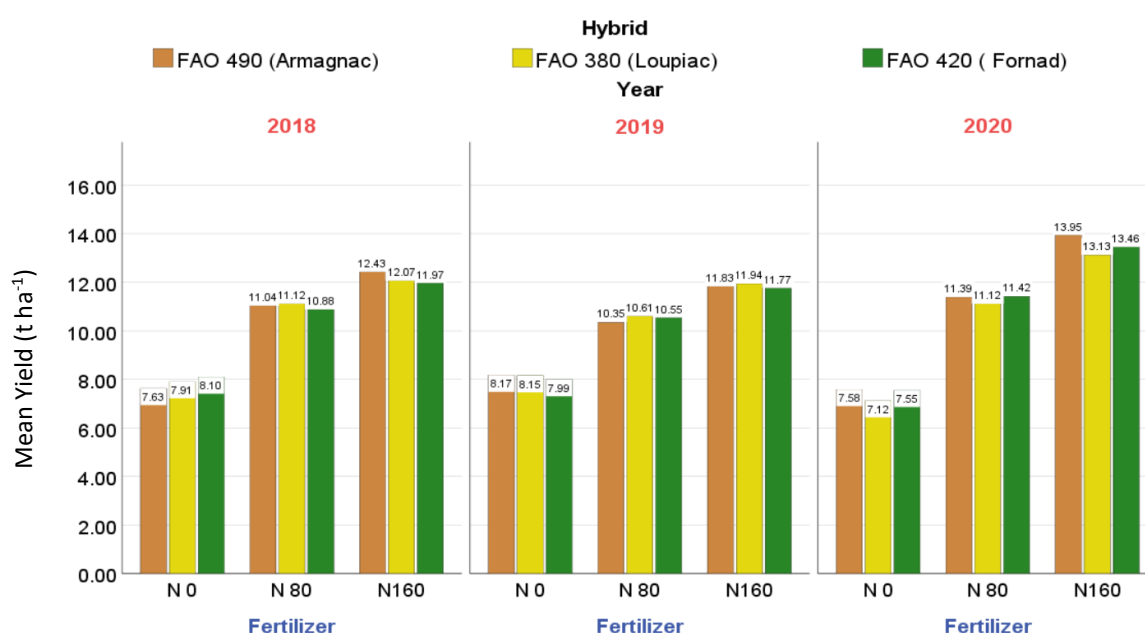


Figure 49. Fertilization x hybrid x crop-year interaction (Debrecen, 2018-2020)

Yield of Armagnac (FAO 490) x N160 in 2020 was 0.82 and 0.56 t ha⁻¹ higher than Loupiac (FAO 380) and Fornad (FAO 420), respectively. The result indicated Armagnac higher yield potential under favorable condition of high nutrient and water supply, as indicated by its higher FAO number. Széles et al. (2019a) also reported similar findings, which showed Armagnac (FAO 490) yield was significantly higher than Renfor (FAO 320) in wet year (2016), compared to year with low rainfall (2017) and attributed it to a better conversion ratio of GSR and fertilizer utilization in wet year.

4.6 EFFECT OF PLANTING DENSITY ON MAIZE YIELD

Plant density x hybrid interaction was significant ($P < 0.05$). Differences in yield among the three hybrids were not significant at 60,000 planting density. However, at 80,000 plant ha⁻¹ in both monoculture and biculture, yield difference between Armagnac (FAO 490) and the other hybrids was statistically significant (Table 23).

Table 23. Yield of hybrids at 60 and 80,000 plants ha⁻¹ (Debrecen, 2018-2020)

Hybrid	Mean yield (t ha ⁻¹)			Yield difference (t ha ⁻¹)		
	60,000 Mono (a)	80,000 Mono (b)	80,000 Biculture (c)	(b) - (a)	(c) - (a)	(c) - (b)
Armagnac (FAO 490)	9.32 ^a	8.80 ^b	13.35 ^b	-0.52	4.03	4.55
Loupiac (FAO 380)	9.41 ^a	9.37 ^a	12.28 ^a	-0.04	2.87	2.91
Fornad (FAO 420)	9.49 ^a	9.36 ^a	12.38 ^a	-0.13	2.89	3.02
Mean	9.41	9.18	12.67	-0.23	3.26	3.49
LSD _{0.05} =0.43 Values with different letters in column differ significantly						

Armagnac (FAO 490) yield was significantly lower than Loupiac (FAO 380) and Formad (FAO 420) in 80,000 (mono), whereas, in 80,000 (biculture) yield was significantly higher. Increasing planting density from 60 to 80,000 plants ha⁻¹ in monoculture plots did not increase yield for any of the test hybrids and suggests that 80,000 plants ha⁻¹ had exceeded the threshold for optimum yield gain.

It can be concluded, therefore, that the optimum planting density for the test hybrids is between 60,000 to 80,000 plants ha⁻¹. The conclusion is in conformity with research findings which showed that increasing planting density, increased yield up to a maximum, beyond which yield decline with any further increase in plant population (Vad et al., 2007; Tokatlidis & Koutroubas, 2004; Pepó & Murányi, 2014; Sárvári, 2005; Sangoi, 2001).

At 80,000 plants ha⁻¹ (biculture), yield of all hybrids were significantly higher than 60 and 80,000 plants ha⁻¹ in the monoculture treatment. Armagnac (FAO 490) yield gain was superior to Loupiac (FAO 380) and Fornad (420). The significantly higher yield of the test hybrids at 80,000 plants ha⁻¹ in biculture buttressed the need to ensure that increasing plant population density is supplemented with the requisite nutrient, in order to realize the full yield potential of the hybrids.

The effect of higher plant population density on individual plant (hybrid) productivity was significant. Individual plant productivity (IPP) for the test hybrids decreased from 60 to 80,000 plants ha⁻¹ in monoculture (fig. 50).

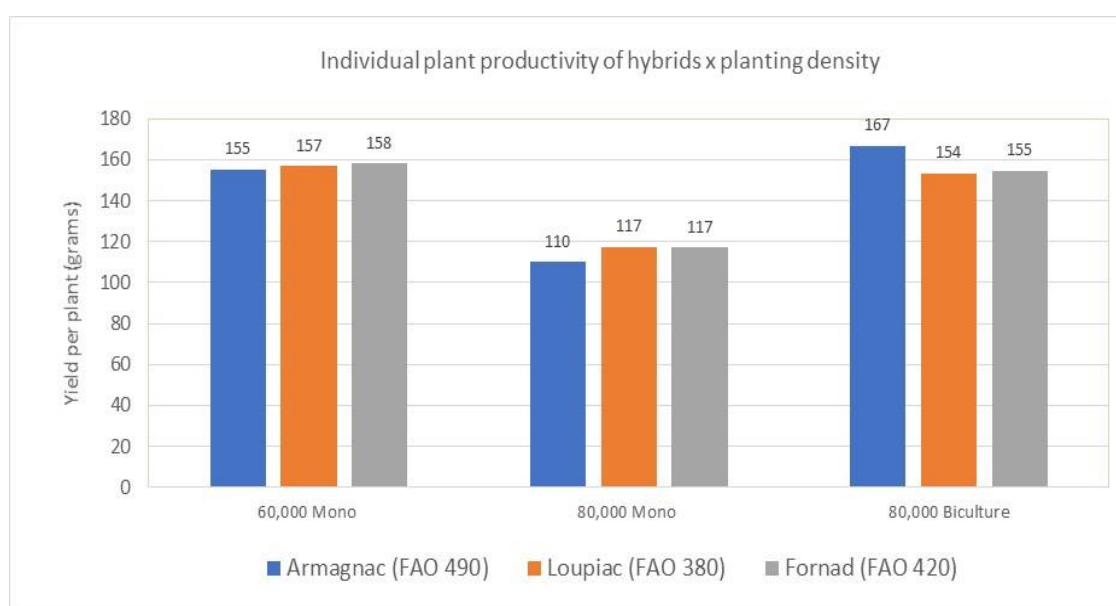


Figure 50. Individual plant productivity for hybrids at 60 and 80,000 plants ha⁻¹ (Debrecen, 2018-2020)

Armagnac IPP decline was highest (-29%), whereas, Loupiac and Fornad decline was almost on par. Since both yield and IPP of all the hybrids decreased at the higher density in monoculture it can be inferred that 80,000 plants ha⁻¹ exceeded the nutritional capacity of the soil. The result is corroborated by findings of Yan et al. (2016), Sangoi (2001), and Sárvári (2005), who found with increasing plant density, the individual plant productivity is reduced, but the yield per unit area increases until the optimal number of plants density is reached.

Armagnac IPP was significantly higher than Loupiac and Fornad in biculture 80,000 plants ha⁻¹, which suggests that Armagnac (FAO 490) is more adaptable than Loupiac (FAO 380) and Fornad (FAO 420) to higher density and nutrient rich soil and can therefore be cultivated at >80,000 plants ha⁻¹ in biculture cropping system. This

observation is consistent with work of Boomsma et al. (2009) and Tollenaar & Wu (1999), who posited that variations in yield responses of hybrids to changes in plant population density, hinges on their ability to tolerate abiotic and biotic stresses, including tolerance to high planting density. Similar report by Bramdeo & Rátonyi (2021), showed that Fornad (FA0 420) was the best performing hybrid at a density of 60,000 plants ha⁻¹, with 5.4% (0.49 t ha⁻¹) higher yield than Armagnac (FAO 490) and 2% (0.19 t ha⁻¹) above Loupiac (FAO 380), while at 80,000 plants ha⁻¹ Armagnac (FAO 490) yield was the highest.

4.6.1 Planting density x irrigation x fertilization interaction

Planting density x irrigation x fertilization interaction was statistically significant ($P < 0.05$). Yield surplus from irrigation was only realized with 80,000 plants ha⁻¹ (biculture) at all levels of fertilization (fig. 51). Yield increase with irrigation was not

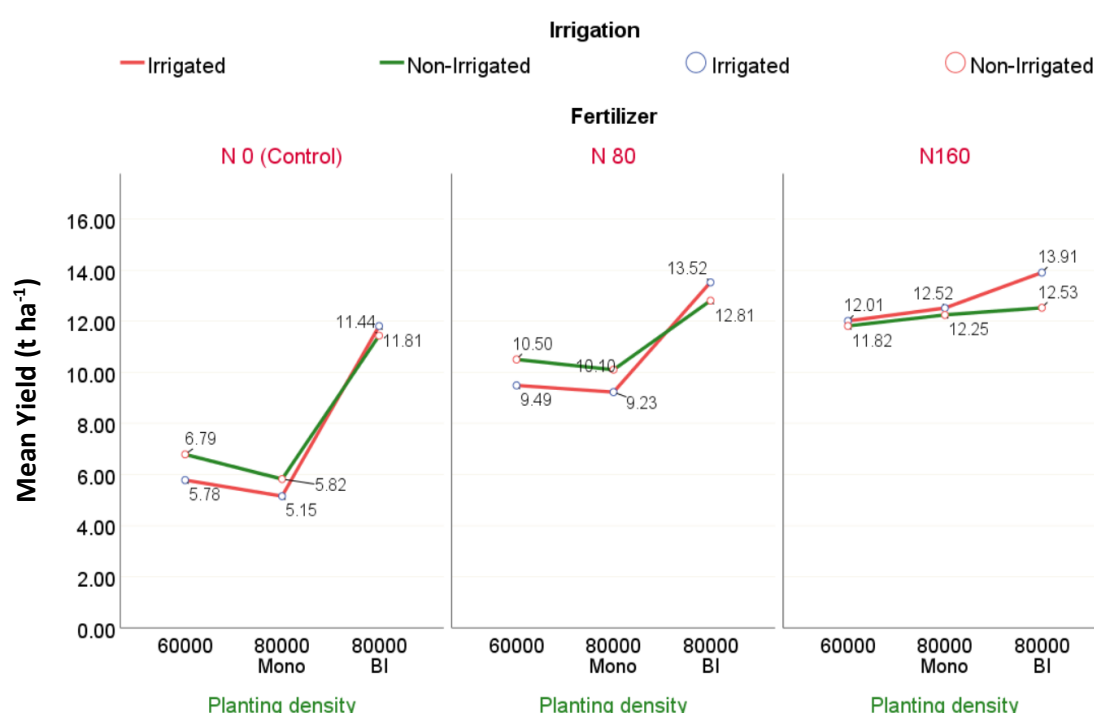


Figure 51. Planting density x irrigation x fertilization interaction (Debrecen, 2018-2020)

significant at N160 x 60 and 80,000 plant ha⁻¹ (mono) and was adversely affected in the control and N80. The results demonstrated that fertilization improves water use efficiency and irrigation was not necessary in monoculture for N0 and N80 treatments. This could be attributed to the low nutrient level of monoculture soil coupled with the favorable water supply of the crop-years during the examined period. Similar

observation was made by Huzsvai & Széles (2009), who concluded that the amount of water supply (precipitation/irrigation) to the maize crop can only be adequately judged based on the nutrient supply. Orfanou et al. (2019), reported that higher plant densities do not always give the highest yield and do not always require higher irrigation amounts. They found that although irrigation improve maize yield, increasing the amount of water does not proportionately increase yield. Similarly, Huynh et al. (2019), found in years with high water availability, the effect of irrigation was marginal. According to Salazar et al. (2012), rainfall (amount and distribution), soil texture and water holding capacity of soil are all factors, which can affect the need for irrigation and therefore impact on crop yield.

4.7 Hybrids yield performance

Hybrids overall mean yield difference were not statistically significant (table 24). The hybrids, however, vary in their response to the different levels of agrotechnological input. Armagnac (FAO 490) yield was significantly higher with winter wheat forecrop compared to Loupiac (FAO 380) and Fornad (FAO 420) , whereas at 80,000 plants ha⁻¹ in monoculture cropping system Armagnac (FAO 490) yield (8.80 t ha⁻¹) was significantly lower than both Loupiac (FAO 380) and Fornad (FAO 420) (fig. 52).

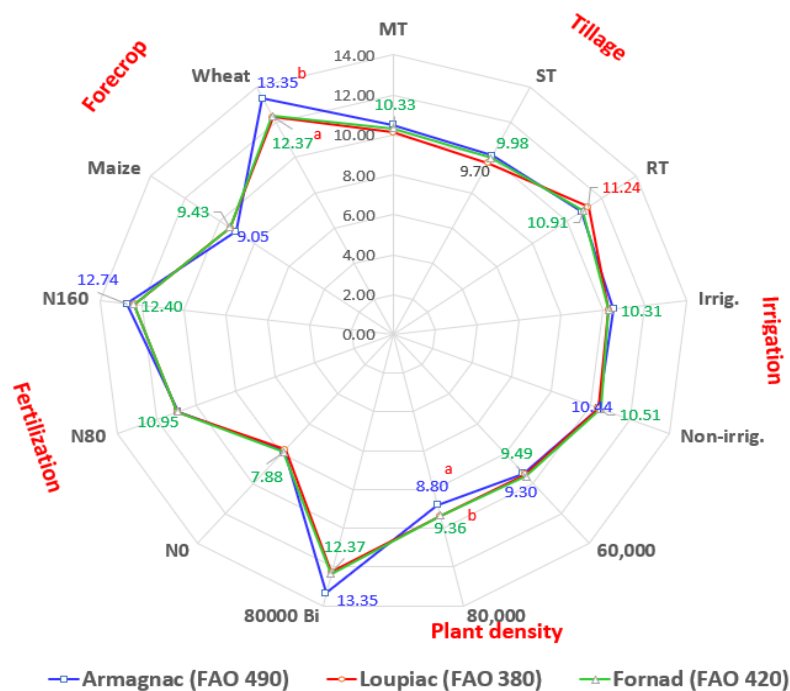


Figure 52. Radar chart of hybrids yield x treatments (Debrecen, 2018-2020)

Armagnac (FAO 490) was most sensitive to high population density in monoculture and low nutrient level (control) as indicated in radar chart (fig. 52).

Table 24. Hybrid yields by various levels of agrotechnical inputs (Debrecen, 2018-2020)

Test hybrids	Yield (t ha ⁻¹)													Mean
	Tillage			Planting density			Fertilization			Forecrop		Irrigation		
	MT	ST	RT	60000*	80000*	80000**	N0	N80	N160	Maize	Wheat	Irrig.	Non-irrig.	
Armagnac (FAO 490)	10.49	10.12	10.84	9.30	8.80 ^b	13.35 ^b	7.79	10.93	12.74	9.05	13.35 ^b	10.53	10.44	7.86 ^a
Loupiac (FAO 380)	10.12	9.70	11.24	9.40	9.37 ^a	12.28 ^a	7.73	10.95	12.38	9.39	12.29 ^a	10.30	10.40	7.82 ^a
Fornad (FAO 420)	10.33	9.98	10.91	9.49	9.36 ^a	12.37 ^a	7.88	10.95	12.40	9.43	12.37 ^a	10.31	10.51	7.86 ^a
	* - monoculture ** -biculture			Values with different letters in column differ significantly (LSD _{0.05})										

Yield differences among the test hybrids in tillage treatments were not statistically significant ($P>0.05$). There was no significant difference in fertilizer use efficiency (FUE) among the test hybrids. Armagnac (FAO 490) preference for biculture cropping system was very evident with significantly higher yields than Loupiac (FAO 380) and Fornad (FAO 420). Irrigation had no significant influence on yield of any of the test hybrids.

Among the treatments' combination, three mega-environments were identified (fig. 53) which showed the preferred treatments for each genotype. All hybrids performed equally

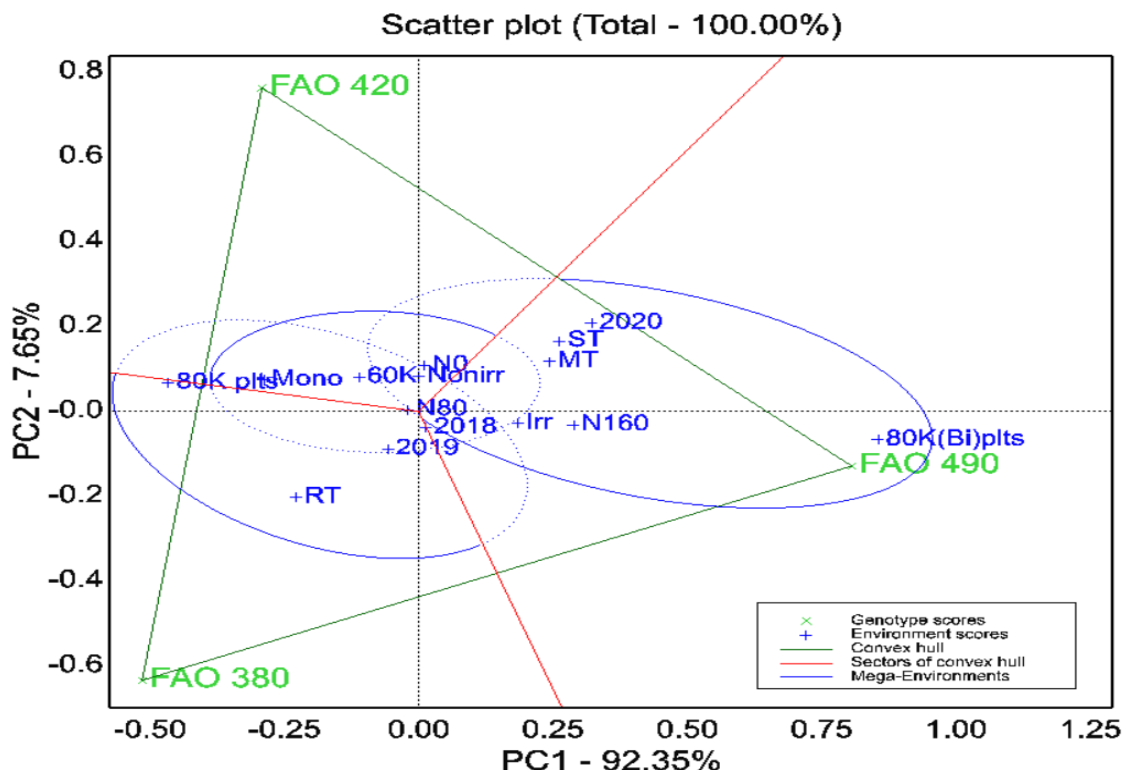


Figure 53. GGE Scatter biplot (which won where) of the test hybrids (Debrecen, 2018-2020)

well with N80 which is indicated at the intersection of the sector lines. Armagnac (FAO 490) performance was best in 2020, irrigated, N160 and at 80,000 plants under biculture cropping system. Fornad (FAO 420) performed better with a plant population of 60,000 in monoculture.

Among the test hybrids, Armagnac (FAO 490) yield was the highest, followed by Fornad (FAO 420), as indicated by their position on the axis (fig. 54). Both hybrids yields were above average, while FAO 380 (Loupiac) yield was below the average (AEC). FAO 380 (Loupiac) however displayed the highest yield stability as indicated by the shortest distance from the axis. This was followed by FAO 420 (Fornad) and FAO 490 (Armagnac), both of which recorded higher yields but had lower yield stability compared to FAO 380 (Loupiac).

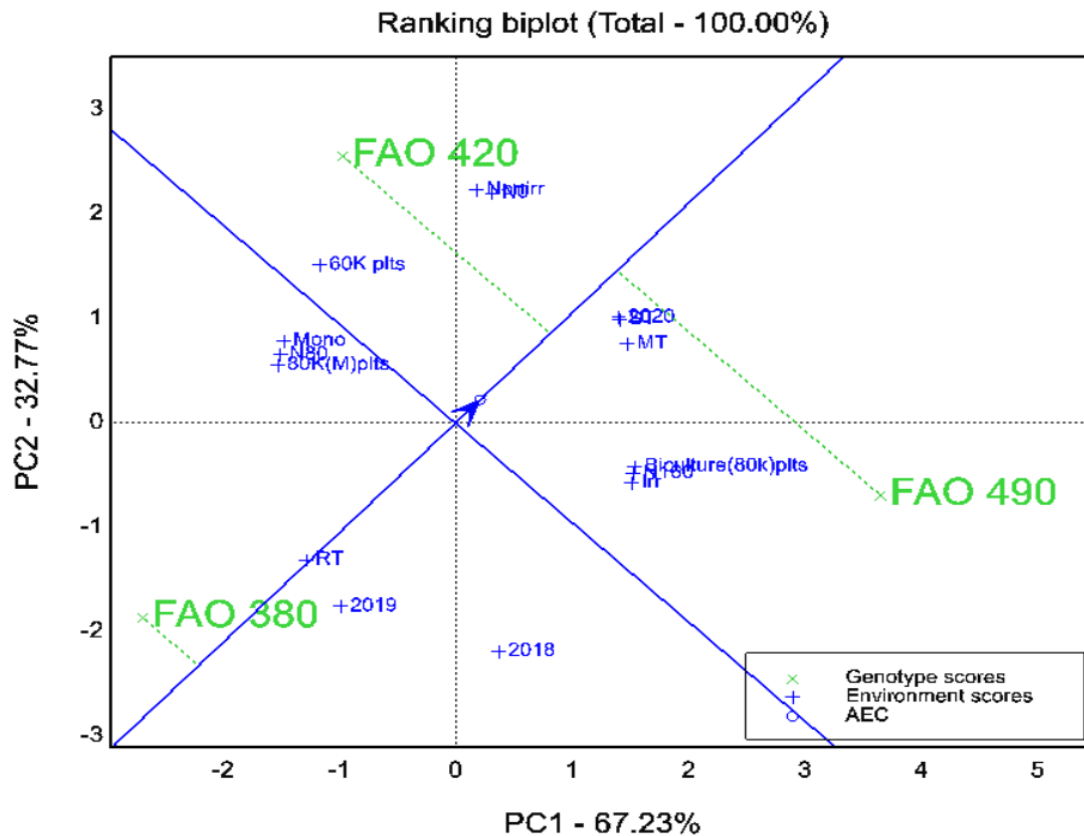


Figure 54. GGE ranking biplot of test hybrids (Debrecen, 2018-2020)

4.7.1 Hybrid x tillage x planting density interaction.

Hybrid x tillage x planting density interaction was significant ($P < 0.05$). At 60,000 plants ha^{-1} yield of the test hybrids were significantly higher in RT (fig. 55). Loupiac (FAO 380) responded positively to higher plant density (80,000 - mono) in RT, whereas

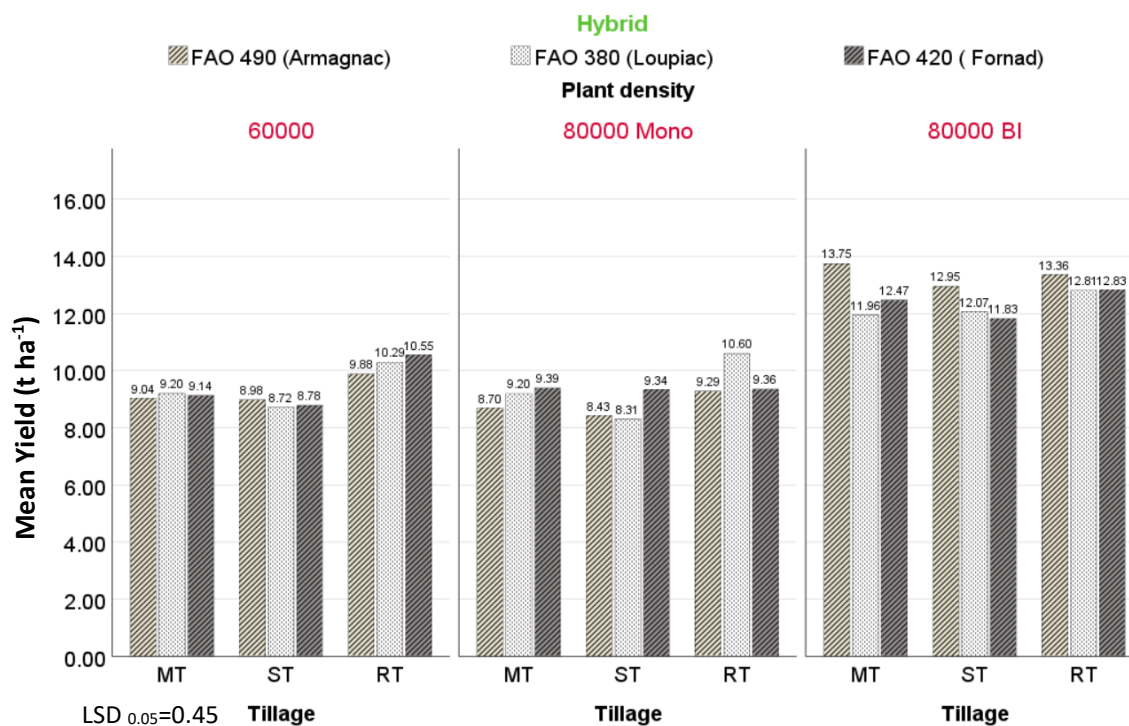


Figure 55. Hybrids x tillage x planting density interaction (Debrecen, 2018-2020)

Armagnac and Fornad showed significant yield decline. Armagnac (FAO 490) yield was significantly higher in all tillage systems at 80,000 plants ha^{-1} under biculture cropping systems. There was no significant difference in yield between the hybrids in ST and MT at 60,000 plants ha^{-1} . The results suggest Loupiac is better adapted to higher density (80,000 mono) under lower nutrient supply in RT, compared to Armagnac and Fornad, whereas, at lower density (60,000 plants ha^{-1}) Fornad yield was significantly higher than Armagnac in RT. The superior performance of Armagnac at 80,000 plants ha^{-1} (bi) in all tillage system suggests it is more suitable for intensive cropping system with higher nutrient and water supply. The results demonstrated the uniqueness of each hybrid's response to different combination of agrotechnological inputs and therefore, synchronizing the agronomic management factors with the needs of the biological base would be fundamental for exploiting the full potential of a given hybrid.

4.7.2 Hybrid x tillage x fertilizer interaction

Hybrid x Tillage x fertilizer x interaction was significant ($P < 0.01$). Loupiac (FAO 380) fertilizer use efficiency (FUE) was highest in RT at N80, while Armagnac (FAO 490) FUE was highest at N160 in all tillage treatments. Yield differences were statistically significant in RT+N160 and ST+N160 between Armagnac (FAO 490) and Fornad (FAO 420); Armagnac (FAO 490) and Loupiac (FAO 380), respectively. Loupiac (FAO 380) FUE was lowest in ST and MT at all fertilization levels and yield differences were statistically significant in MT+N0 (control), ST+N80 and ST+N160. There was no significant difference between Armagnac (FAO 490) yield in MT and RT of the control (N0) and suggests that deep tillage (RT) did not influence the yield performance of the hybrid (fig. 56). Both Loupiac (FAO 380) and Fornad (FAO 420) yield was significantly higher in RT x N0 (control), compared to MT x N0 (control) and confirm these hybrids preference for deep tillage and natural nutrient reserve, compared to Armagnac (FAO 490). The highest FUE of Armagnac (FAO 490) in all tillage treatments with N160 also suggests the hybrid's potential for improving yield with increase fertilizer dosages, while simultaneously minimizing the risk associated with nitrate leaching. The significant increase in yield of the hybrids with higher fertilizer dosage in all tillage treatments is also in conformity with several research findings, which showed fertilization was responsible for the largest incremental yield gain, compared to tillage and genotype.

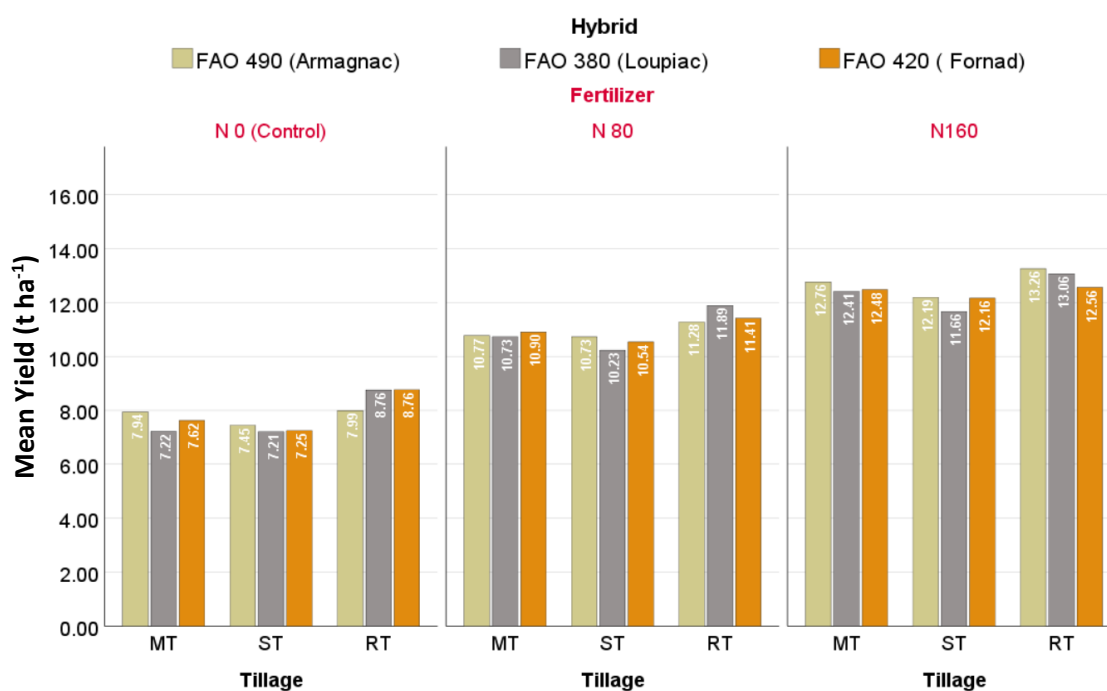


Figure 56: Tillage x fertilization x hybrids interaction (Debrecen, 2018-2020)

4.8 Effect of agrotechnological factors on grain nutritional content

4.8.1 Tillage practices

Tillage practices had no significant effect on grain nutritional content. Grain protein, starch and oil contents varied among tillage treatments with no significant difference among treatments ($P>0.05$). Protein content was highest in RT, whereas, starch and oil content were highest in ST (table 25).

Table 25. Tillage treatments grain protein, oil and starch content (Debrecen, 2018-2020)

Tillage treatments	Grain nutritional content (%)		
	Protein (%)	Starch (%)	Oil (%)
Mouldboard tillage (MT)	9.32	72.86	4.69
Strip tillage (ST)	9.30	73.01	4.83
Ripper tillage (RT)	9.55	72.62	4.78
LSD _{0.05}	0.36	0.41	0.30
value with different letters in column differ significantly (LSD _{0.05})			

In similar research, Simić et al. (2020), reported no significant difference in grain oil and starch content among tillage systems but found grain protein was significantly higher in conventional tillage, compared to reduced and non-till. The difference in results could be attributed to a combination of factors, which include difference in tillage practices, genetic makeup of the test hybrids, soil fertility, as well as, the agroecological conditions, all of which can influence grain nutritional content. In Japan, Shinoto et al. (2018), observed that even though silking occurred a bit earlier and root lodging was lower in plowing than in rotary tilling, there was no significant difference in starch and crude protein content.

The overall yield of starch, protein and oil for the respective tillage system remain in the same order as grain yield ($RT>MT>ST$) (table 26).

Table 26. Tillage systems yield of starch, protein and oil (Debrecen, 2018-2020)

	Mean grain	Percent per 100 g of grain			Yield per hectare (kg)		
	Yield (t ha ⁻¹)	Starch	Protein	Oil	Starch	Protein	Oil
MT	10.32	72.86	9.32	4.69	7519	962	484
ST	9.93	73.01	9.30	4.83	7250	923	480
RT	11.00	72.62	9.55	4.78	7988	1051	526

The result demonstrated that tillage practices have more influence on overall grain yield, rather than concentration of the grains' nutritional content. This observation is in harmony with report by Houx et al. (2016) & Lyon et al. (1998), who found tillage

systems had no significant effect on grain nutritional content and was not a dominant factor influencing composition of maize grain. The results also concurred with findings of Andrija et al. (2009), who reported that protein content of maize grains can be improved with the application of more intensive tillage, together with more favorable physical and chemical properties of soil, compared to minimum tillage.

4.8.2 Fertilization effect on grain nutritional content

Among the agrotechnological factors, fertilization impact on grain nutritional was most significant ($P<0.05$). At all levels of fertilization treatments, differences between starch and protein content (%) were significant ($P<0.05$). Oil content was not significantly influenced by fertilization treatments, although the percent oil was highest in N160. Grain protein content positively correlated with fertilization, whereas, the starch content showed a negative correlation (fig. 57).

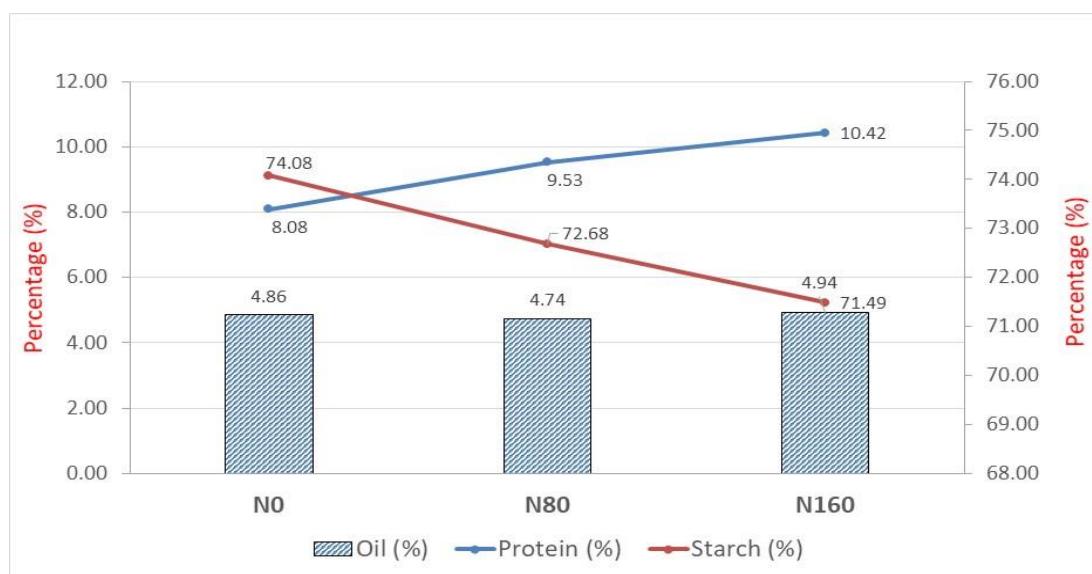


Figure 57. Effect of fertilization on starch, protein, and oil content of maize grain (Debrecen, 2018-2020)

Protein concentration was the lowest in the control (N0) and increased significantly with N80 & N160. It is well established that Nitrogen is an essential component of protein, hence the positive correlation between N fertilization and grain protein content was expected. Oil content was lower in N80, compared to N160. Similar findings by Wasaya et al. (2018), showed that unlike the protein content, which has a positive correlation with N-fertilizer, the oil and starch was negatively correlated. Rehman et al. (2020),

Erdei et al. (2013) & Simić et al. (2020), reported similar results which showed protein content in maize grains significantly increased with increase N application, while starch was negatively and significantly affected.

4.8.3 Effect of irrigation on grain nutritional content

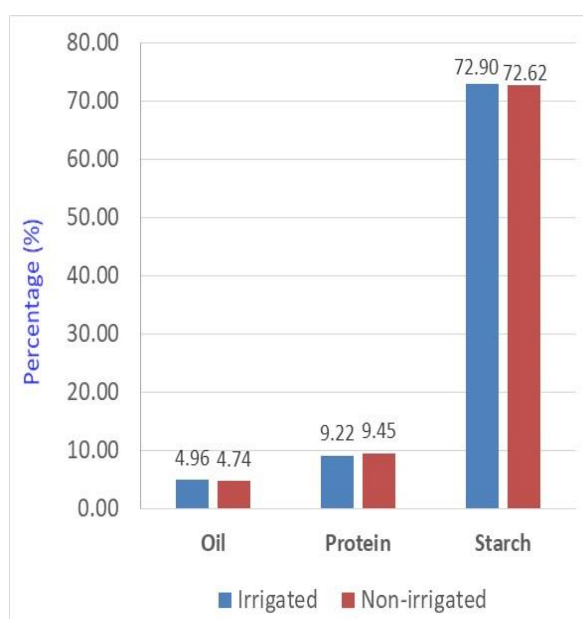


Figure 58a. Effect of irrigation on oil, protein & starch content of maize grain (Debrecen, 2018-2020)

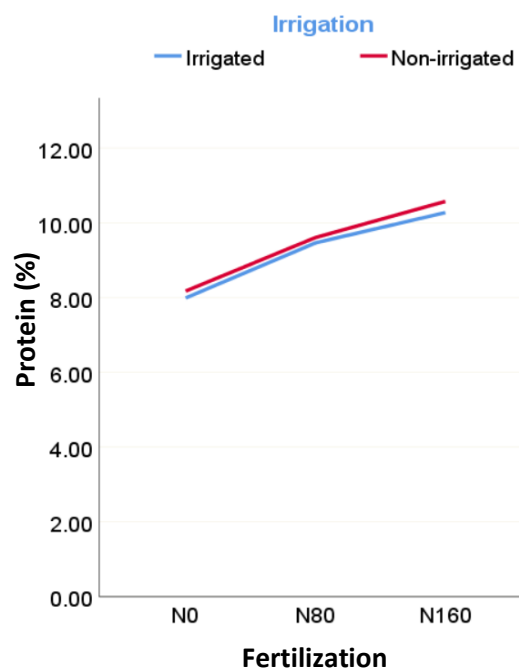


Figure 58b. Effect of fertilization x irrigation interaction on grain protein (%) (Debrecen, 2018-2020)

Irrigation impacted negatively on protein content and positively on both starch and oil content, however differences were not statistically significant ($P > 0.05$) (fig. 58a). Irrigation x fertilization interaction impacted negatively on grain protein content. Protein content of grain decreased with irrigation in both the control (N0) and fertilized treatments (fig. 58b). Similar observations were made by Virág et al. (2020), who reported protein content of maize hybrids decreased with irrigation, while starch content increased but differences were not statistically significant. The result is also consistent with findings of Kresović et al. (2018), who reported highest oil content of maize under full irrigation compared to rainfed. Széles & Nagy (2012), similarly observed that in the wet year the protein content of maize was lower than in dry year.

4.8.4 Effect of plant density on grain nutritional content

Planting density had no significant effect on grain nutritional content ($P>0.05$). Grain protein content was significantly higher at 80,000 plants ha^{-1} (biculture), compared to 60 and 80,000 plants ha^{-1} (mono) (Table 27).

Table 27. Planting densities grain protein, oil and starch content (Debrecen, 2018-2020)

Planting density	Grain nutritional content (%)		
	Protein (%)	Starch (%)	Oil (%)
60,000 plts/ha (Mono)	9.06 ^a	73.01 ^a	4.60
80,000 plts/ha (Mono)	8.97 ^a	73.49 ^b	4.73
80,000 plts/ha (Biculture)	9.56 ^b	72.91 ^a	4.65
LSD _{0.05}	0.29	0.46	0.34
value with different letters in column differ significantly (LSD _{0.05})			

Plant density correlation with grain starch content was significant (table 28). Starch content at 80,000 plants ha^{-1} (mono), was significantly higher than 60 (mono) and 80,000 plants ha^{-1} (biculture). There was no significant difference in oil content among the different planting densities. Virág et al. (2020), also reported a positive but non-significant correlation between planting density and starch content.

The higher protein content at 80,000 plant ha^{-1} in biculture plots could be attributed to the higher fertility status of soil in biculture cropping system. The non-significant impact of planting densities on grain nutritional content agrees with report by Bernhard & Below (2020), who found changes in plant population generally did not have any significant effect on grain quality. The result also concurred with findings of Rafiq et al. (2010), who reported that protein content of maize decreased at higher plant densities, as evident in table 27 between 60 and 80,000 plant ha^{-1} (mono). Contrasting findings by Lihang & Luminkewas (2017), showed that maize planted at lower density produced higher starch and sugar content. The difference in results could be attributed to several factors which influence grain nutritional content such as, agroecological condition, soil fertility and genetic makeup etc.

Table 28. Pearson's correlations: agrotechnological factors x grain nutritional contents (Debrecen, 2018-2020)

Pearson's correlation: Agrotechnological factors x Oil x Protein x Starch content of maize grains										
		Tillage	Irrigation	Forecrop	Hybrid	Fertilizer	Plant density	Oil	Protein	Starch
Tillage	Pearson Correlation	1	-0.048	0.006	0.004	0.000	-0.007	-0.002	0.008	-0.057
	Sig. (2-tailed)		0.102	0.839	0.895	0.998	0.808	0.953	0.788	0.051
	N		1170	1170	1170	1170	1170	1170	1170	1170
Irrigation	Pearson Correlation		1	0.005	-0.001	0.012	-0.036	-0.047	0.049	-0.021
	Sig. (2-tailed)			0.855	0.968	0.691	0.221	0.105	0.091	0.469
	N			1170	1170	1170	1170	1170	1170	1170
Forecrop	Pearson Correlation			1	0.015	-0.003	.484**	0.006	.064*	-0.016
	Sig. (2-tailed)				0.617	0.912	0.000	0.826	0.029	0.593
	N				1170	1170	1170	1170	1170	1170
Fertilizer	Pearson Correlation					1	-0.001	0.015	.377**	-.279**
	Sig. (2-tailed)						0.961	0.612	0.000	0.000
	N						1170	1170	1170	1170
Plant density	Pearson Correlation						1	-0.009	0.051	.152**
	Sig. (2-tailed)							0.770	0.079	0.000
	N							1170	1170	1170
Oil	Pearson Correlation							1	-0.001	-.072*
	Sig. (2-tailed)								0.961	0.014
	N								1170	1170
Protein	Pearson Correlation								1	-.151**
	Sig. (2-tailed)									0.000
	N									1170
Starch	Pearson Correlation									1
	Sig. (2-tailed)									
	N									1170

** . Correlation is significant at the 0.01 level (2-tailed). * . Correlation is significant at the 0.05 level (2-tailed).

4.8.5 Effect of crop rotation on grain nutritional content

Crop rotation impact on grain nutritional quality was not statistically significant ($P > 0.05$). Forecrop correlated positively with grain protein content and was significant (table 28). The higher protein content with winter wheat forecrop could be attributed to the higher fertility of biculture soils and concurred with findings by Mahama (2018) and Negash et al. (2018), which showed protein content of maize grains was significantly higher in biculture treatment plots.

4.8.6 Hybrids grain nutritional content

Genotypes impact on grain nutritional content was significant ($P < 0.05$). Starch content was significantly higher in Loupiac (FAO 380), compared to Fornad (FAO 420) and Armagnac (FAO 490), whereas, Armagnac grain protein content (9.58%) was higher than Loupiac (9.30%) and Fornad (9.20%) and statistically significant (table 29).

Table 29. Hybrids grain protein, oil and starch content (Debrecen, 2018-2020)

Hybrid	Grain nutritional content (%)		
	Protein (%)	Starch (%)	Oil (%)
Armagnac (FAO 490)	9.58 ^b	72.51 ^a	4.63
Loupiac (FAO 380)	9.28 ^a	73.80 ^b	4.79
Fornad (FAO 420)	9.21 ^a	72.29 ^a	4.94
LSD _{0.05}	0.37	0.41	0.32
value with different letters in column differ significantly (LSD _{0.05})			

Hybrid grain nutritional content was influenced by the level of agrotechnological inputs, specifically fertilization. Protein content increased with increase in fertilizer dosage (fig. 59a). Armagnac protein content was significantly higher than Loupiac (FAO 380) and Fornad (FAO 420) with N80 fertilization. Starch content of grain decreased with increased fertilizer dosage for all the hybrids (fig. 59b).

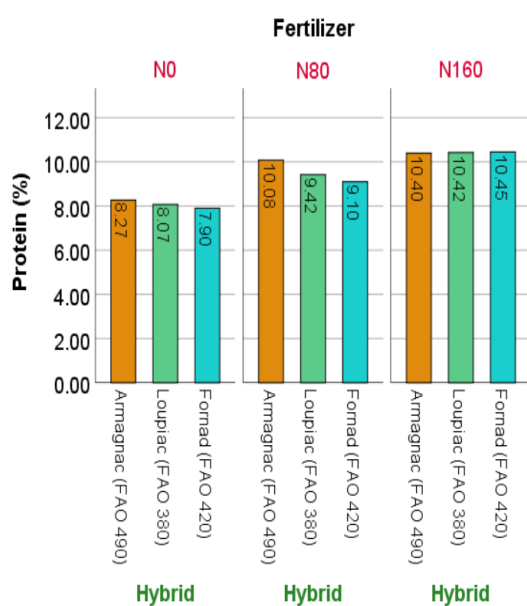


Figure 59a. Grain protein content of hybrid x fertilization (Debrecen, 2018-2020)

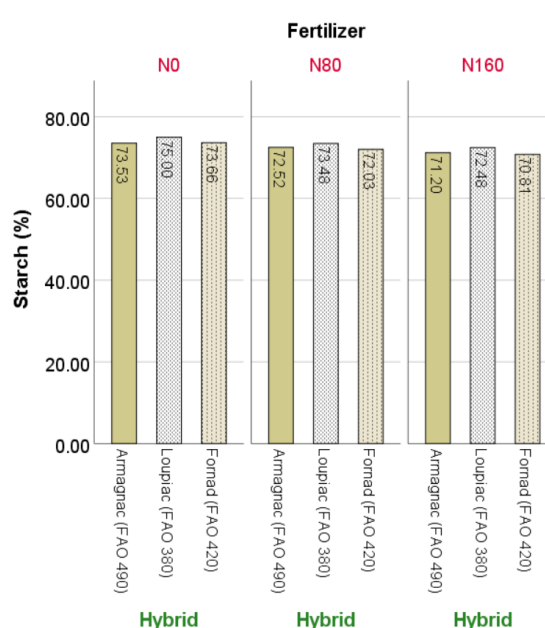


Figure 59b. Grain starch content of hybrid x fertilization (Debrecen, 2018-2020)

Loupiac (FAO 380) starch content was highest at all fertilization levels (fig.59b), followed by Fornad (FAO 420) and differences were statistically significant.

5. CONCLUSIONS, SUGGESTIONS

- Ripper tillage is best suited for monoculture cropping system, whereas moldboard tillage is more conducive for biculture cropping system. The higher fertility of biculture soils compromised the deep-tillage effect.
- Fertilization and crop rotation significantly enhanced grain yield and protein content of maize grains. Soil fertility (nitrogen fertilization) is essential not only for grain yield but also for improving the protein concentration of maize grains.
- The optimum planting density is between 60 and 80,000 plants ha⁻¹. Concluding that 70,000 plant ha⁻¹ (midpoint) is the ideal density would not be improbable and is supported by earlier research findings. Increasing
- An increase in plant density will increase yield, provided the nutrient supply is adequately met. Higher (increase) planting density improves fertilizer use efficiency (FUE) and can help to minimize N-pollution.
- Under favorable growing conditions (such as 2020) the treatment combination which delivers the best result is biculture cropping system x MT x N160 x Armagnac (FAO 490) x 80,000 plants ha⁻¹, while in monoculture in average crop-year, ripper tillage x N80 x Fornad (FAO 420) x 60,000 plants ha⁻¹ will give optimal result.
- Loupiac (FAO 380) showed preference for ripper tillage and had the highest yield stability. It appears well suited for less favorable conditions compared to Armagnac (FAO 490) and Fornad (FAO 420).
- The significantly higher yield of RT in the control of monoculture plots in all the examined years indicates the depth of fertility of the chernozem soil at the experimental site. Accounting for the non-fertiliser nitrogen (natural) is essential to avoid excess fertilizer application and to help customize the agronomic input to meet the nutritional needs of the specific hybrid. This will also allow for improvement in the nitrogen use efficiency, minimize N-leaching and enhance crop production efficiencies. It also confirms maize preference for deep tillage and the plant's ability to reach deeper in the soil profile once the condition is conducive. Further testing will be needed to quantify the available natural nutrient reserved beyond the usual 30 cm depth and this can also help in tailoring the applied fertilizer dosage to further improve the production efficiencies.

- Scarcity of water supply due to climate variability and increase frequency of drought years requires improvement in water use efficiency to sustain yields. This can be achieved through the use of strip or ripper tillage, as alternatives to conventional mouldboard tillage, coupled with suitable crop rotation, which will also augment the production efficiency of maize.
- Fornad (FAO 420) was the best performing hybrid at 60,000 plants ha⁻¹ with the highest productivity per plant and water use efficiency, thus showing suitability for condition of reduced soil moisture (drought). Loupiac (FAO 380) was the most stable hybrid at 80,000 plants and responded best to natural nutrient reserve of the soil, with similar water use efficiency as Fornad (FAO 420).
- Armagnac (FAO 490) recorded the highest yield declined from 60 to 80,000 plant in monoculture cropping, whereas in biculture, it recorded the highest incremental gain, compared to Fornad (FAO 420) and Loupiac (FAO 380). It responds best to favorable conditions (high nutrient and water supply) and appears best suited for intensive cropping system.
- The highest yield was obtained at N160 under irrigation treatment. The result accentuates the need for synchronizing fertilization and irrigation. The yield penalty of irrigation in the control (N0) also reinforces the need for harmonization of water supply with nutrient supply.
- The soil at the experimental site is of high fertility, as evident from yield in the control (7.80 t ha⁻¹); compared to World's average yield of 5.92 t ha⁻¹ (FAO STAT 2020). The high fertility can buffer for shortfall in applied agrotechnique, hence, different effect size might be obtained if this research is replicated under different agroecological conditions with the same levels of production technology.
- The results demonstrated that crop management factors influenced grain yield and nutritional content of the test hybrids to varying extent. The degree of influence depends on the nature of the applied agrotechnology, as well as the treatment levels, prevailing weather condition of the specific crop year and the genetic makeup of the test hybrid.
- Compared to the genotype and environmental conditions, the farming practices and level of agrotechnology provide greater flexibility for manipulation and therefore, with sound agronomic management practices, (i.e. matching the agrotechnological factors with the needs of the biological base and agroecological conditions) adverse effect of weather can be mitigated and the desired yield outcomes can be achieved with minimal environmental consequences.

6. NEW SCIENTIFIC RESULTS

- Mean yield of RT in monoculture was 10% ($+0.89 \text{ t ha}^{-1}$) higher than MT, whereas in biculture there was no significant difference between the two tillage treatments ($13.00 \text{ vs. } 12.72 \text{ t ha}^{-1}$; $P>0.05$). The higher soil fertility of biculture, as indicated by the significantly higher yield in the control, compared to monoculture ($N0=11.62 \text{ t ha}^{-1} \text{ vs. } N0=5.89 \text{ t ha}^{-1}$) compromised the potential of ripper tillage (RT) to increase root access to nutrient reserve in the lower soil profile (30-60 cm range). Thus, ripper tillage (RT) was found to be more suitable for monoculture cropping system, whereas moldboard tillage (MT) was more conducive for biculture cropping system.
- Ripper tillage (RT) fertilizer use efficiency (FUE) was 5.0-10.7% higher than Moldboard (MT) and Strip tillage (ST), whereas the Agronomic Efficiency (AE) of both MT and ST was 9.6-11.5% higher than RT. The higher FUE of RT suggests it was better able to utilize soil residual nutrient (N), while the higher AE of MT and ST indicate better utilization from applied fertilizer, compared to RT. Ripper tillage can recover a minimum of 24 kg N from the deeper soil profile at the experimental site, since yield in the control($N0$) of monoculture plot exceeded MT by 1.02, 0.95 & 1.29 t ha^{-1} in 2018,2019,2020 respectively.
- Winter wheat forecrop significantly enhanced the yield of all hybrids (31-47%) in all tillage systems with yield increment being highest in Armagnac (FAO 490) ($47\%= 4.30 \text{ t ha}^{-1}$), followed by Fornad (FAO 420) and Loupiac (FAO 380) with 2.94 and 2.89 t ha^{-1} respectively.
- Winter wheat forecrop significantly improved the yield performance of strip tillage (ST). Yield surplus in strip tillage (ST) x biculture was 23% ($+2.28 \text{ t ha}^{-1}$) higher than Ripper (RT) and 35% ($+3.17 \text{ t ha}^{-1}$) above Moldboard tillage (MT) in monoculture maize.
- Each hybrid has a unique environment in which it performs best:
 - Armagnac (FAO 490) yield was highest (13.75 t ha^{-1}) under biculture cropping system x $N160$ x $80,000 \text{ plants ha}^{-1}$ and surpassed Loupiac (FAO 380) and Fornad (FAO 420) by 5% (0.62 t ha^{-1}) and 8% (0.98 t ha^{-1}) respectively.

- Loupiac (FAO 380) yield exceeded Armagnac (FAO 490) and FAO (FAO 420) by 18% (1.72 t ha^{-1}) and 13% (1.27 t ha^{-1}) respectively, in ripper tillage (RT) x N80 x biculture x 80,000 plants ha^{-1} .
- Fornad (FAO 420) yield was superior to both Loupiac (FAO 380) and Armagnac (FAO 490) by 6% (0.47 t ha^{-1}) and 17% (1.24 t ha^{-1}) respectively, in the control (N0) x non-irrigated x Ripper tillage x 60,000 plants ha^{-1} . Armagnac (490) was most sensitive to higher density (80,000 plants ha^{-1}) and lower nutrient status (N0) and recorded the lowest yield (4.92 t ha^{-1}), compared to Fornad (FAO 420) = 5.63 t ha^{-1} and Loupiac (FAO 380) = 5.92 t ha^{-1} . This hybrid responds best to intensive management practices.
- Loupiac (FAO 380) showed the highest yield stability across all treatments with a CV of 30%, compared Fornad (FAO 420) and Armagnac (FAO 490) with 39 and 43% respectively.
- Higher levels of nutrient supply in favorable crop-year had greater yield increasing effect. N160 yield surplus in 2020 which recorded the highest growing season rainfall (442 mm) was 1.66 and 1.35 t ha^{-1} higher than 2019 (290 mm rainfall) and 2018 (318 mm rainfall), respectively.
- Agronomic nitrogen use efficiency (AE) was higher at 80,000 plants ha^{-1} (N80=52%; N160=43%) in monoculture, compared to 60,000 plants ha^{-1} (N80=46%; N160=35%). Biculture AE was significantly lower (N80=19%; N160=10%) compared to monoculture.
- The best treatment combination for favorable crop-year with above average precipitation ($>300 \text{ mm}$) is: biculture cropping system x moldboard tillage x N160 fertilization x Armagnac (FAO 490) x 80,000 plants ha^{-1} , while in monoculture cropping system in average crop-year ($\approx 300 \text{ mm}$ rainfall): ripper tillage x N80 x Fornad (FAO 420) x 60,000 plants ha^{-1} will give optimum result.

7. PRACTICAL UTILIZATION OF RESULTS

- Soil infiltration rate, moisture and penetration resistance varied among tillage practices and provides an indication of the soil physical properties which can allow for the proper selection of tillage implements for removal of root restricting layers and conservation of moisture if necessary. Ripper tillage for example, becomes necessary if infiltration rate of the soil is below the average $<10 \text{ mm hr}^{-1}$ and penetration resistance exceed 3.5 MPa at field capacity.
- Integrating a suitable crop rotation system such as winter wheat forecrop in maize production can reduce the dependency on synthetic fertilizer and minimize risks associated with pollution (N leaching). In this research for example, there was no significant difference in yield between N80 and N160 treatments in biculture (13.17 vs. 13.22 t ha⁻¹). Hence, winter wheat forecrop can eliminated the need for N160 treatment and deliver similar results with N80, thereby reducing the volume of applied fertilizer (-80 kg N) in the environment.
- The significantly higher yield surplus of ripper tillage (+0.96 t ha⁻¹) over MT and ST in the control(N0) of monoculture plot can be buffer for a reduction of 24 kg N ha⁻¹, assuming 25 kg N per ton of grain. This can reduce operational costs by at least, 1,608 HUF per ha (24 kg N @ 67 HUF kg⁻¹) and minimize risk of N leaching. However, there is a need to ascertain the amount of available nutrients in the lower soil profile (30-60 cm).
- ST moisture was 27% higher than MT and 18% above RT in the 0-30 cm range. The higher moisture content of the soils in strip tillage, followed by ripper tillage, provides scope for both tillage systems to be substituted for conventional moldboard plowing during drought condition to aid in conservation of soil moisture and save on applied irrigation.
- The yield surplus of strip tillage (ST) in tandem with crop rotation (+3.52 t ha⁻¹) can significantly reduce costs of operation and improve production efficiency. The yield surplus of ST with crop rotation can generate revenue of 235,840 HUF (3.52 t @

67,000 HUF t grain⁻¹) and offset 80 kg N ha⁻¹, since yield difference between N80 and N160 in ST-biculture was not significantly different (12.73 vs. 12.98 t ha⁻¹).

- Fertilizer use efficiency (NUE) can be used as a determining factor in matching planting density and fertilizer dosages, both from an economical as well as environmental standpoint. For example, in this research the Agronomic nitrogen use efficiency of 19 % with N80 and 10% with N160 in biculture suggests that the planting density (80,000 plants ha⁻¹) was below the threshold for optimum yield or vice-versa the soil fertility was higher. Hence, the fertilizer dosage could be correspondingly reduced, or the plant population increased to achieve higher efficiency levels.
- Agrotechnological inputs can be tailored to suit prevailing agroecological conditions to facilitate more efficient utilization of resources and realization of optimal yield. Example, applying lower (N80) fertilizer dosages in crop-year, with lower levels of rainfall (<300 mm growing season rainfall), while higher dosages (N160) can be applied in favorable year (>400 mm growing season rainfall).

8. SUMMARY

This dissertation presents the findings of the effect of crop management factors (agrotechnological) on the yield, as well as the grain nutritional content (starch, protein, oil) of three hybrids of maize, Armagnac (FAO 490), Loupiac (FAO 380) and Fornad (FAO 420) under the prevailing weather condition of the specific crop year- 2018/2020.

The agronomic factors evaluated include three tillage treatments (Moulboard plowing-MT; Strip tillage -ST, Ripper tillage -RT), three levels of N-fertilizer treatments (N0, N80, N160 kg ha⁻¹), two levels of plant densities (60,000 & 80,000 plants ha⁻¹), irrigated and non-irrigated, monoculture maize and maize-winter wheat biculture. The plant density in the biculture cropping system was a standard 80,000 whereas, both 60 and 80,000 were in monoculture cropping system.

The experiment was set up in a split-plot design and is part of an ongoing long-term polyfactorial experiment at Látókép Research Station of the University of Debrecen, Hungary.

The obtained results are summarized as follows:

- Ripper tillage (RT) delivers best result in monoculture cropping with lower nutrient status and higher bulk density, while MT tillage performs best in biculture maize, with adequate water and nutrient supply (Monoculture: RT>MT>ST; Biculture: MT>RT>ST).
- Strip tillage (ST) yield was lowest among the three tillage systems. Strip tillage recorded the highest moisture level, followed in decreasing order by RT and MT. The semi-arid prevailing type climate in Hungary and increase frequency of drought years, provide an opportunity for ST and RT to be utilized for soil moisture conservation in sustainable maize production.
- Crop rotation improves yield and yield stability and can compensate for a reduction in applied fertilizer dosage of atleast 54 kg N ha⁻¹, with assumption of 25 kg N t⁻¹ grain.
- Increase plant density from 60 to 80,000 plants ha⁻¹ in monoculture lead to decrease in both overall yield and individual plant productivity and suggest that 80,000 plants ha⁻¹ exceeded the optimum threshold.

- Yield of 80,000 plants in biculture cropping system was significantly higher than the same population in monoculture. The results demonstrated that concomitant with increase in plant density, soil fertility must also be improved to achieve optimum yield benefits.
- Irrigation of control plots ($N_0 \text{ kg ha}^{-1}$) in monoculture resulted in yield depression, while in biculture yield improved due to the difference in soil nutrient status and thus, highlighted the need for synchronizing nutrient and water supply.
- Nitrogen and water use efficiency was modified by the prevailing weather condition of the crop-year. In year with highest rainfall water use efficiency was lowest, whereas Nitrogen use efficiency was highest.
- Nitrogen fertilizer is essential for achieving high yield in maize production system. The highest yield was achieved with $N-160 \text{ kg ha}^{-1}$ under irrigated condition, while the lowest yield was obtained in the control ($N-0 \text{ kg ha}^{-1}$). The higher yield in the irrigated treatment highlighted the positive correlation between fertilization and irrigation.
- $N80 \text{ kg ha}^{-1}$ was the optimum level of fertilization with NUE exceeding $N160$ by 33%. Likewise, the fertilizer costs to produce a unit of grain is 33% higher with $N160$.
- Among the agrotechnological factors evaluated, fertilization had the largest impact on grain yield as well as the nutritional content of grains, particularly the protein concentration. Yield variance for fertilization was 39.9%, followed by forecrop (26.5 %), planting density (9.6%), hybrid (0.3%), tillage (3.4%) and irrigation (0.1%) (fig.60).

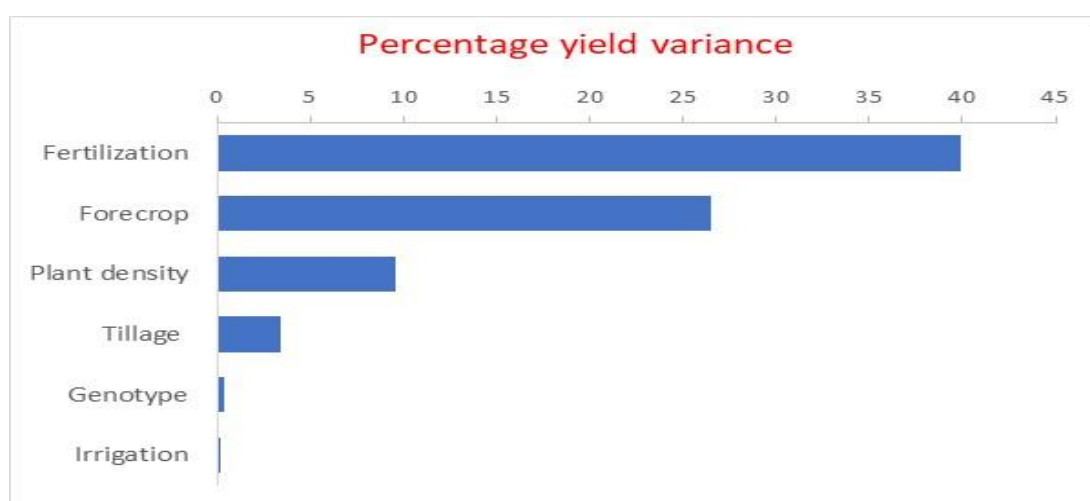


Figure 60. Bar Chart percent yield variance of agronomic factors (Debrecen, 2018-2020)

Table 30: Summary of treatment effects on grain yield & nutritional contents (Debrecen, 2018-2020)

Effect of agrotechnological factors on grain yield and nutritional content of maize					
		Grain Yield (t ha ⁻¹)	Protein (%)	Starch (%)	Oil (%)
Tillage	MT	10.32 ^a	9.32	72.86	4.69
	ST	9.93 ^b	9.30	73.01	4.83
	RT	11.00 ^c	9.55	72.62	4.78
	LSD_{0.05}	0.33	0.36	0.41	0.30
Fertilization	N0	7.80 ^a	8.08 ^a	74.08 ^a	4.86
	N80	10.94 ^b	9.53 ^b	72.68 ^b	4.74
	N160	12.51 ^c	10.42 ^c	71.49 ^c	4.94
	LSD_{0.05}	0.26	0.34	0.40	0.31
Forecrop	Mono	9.29 ^a	9.04 ^a	73.32	4.84
	Biculture	12.67 ^b	9.55 ^b	72.98	4.85
	LSD_{0.05}	0.30	0.32	0.37	0.27
Planting density	60,000	9.40 ^a	9.06 ^a	73.01 ^a	4.60
	80,000 (mono)	9.18 ^a	8.97 ^a	73.49 ^b	4.73
	80,000 (biculture)	12.67 ^b	9.55 ^b	72.98 ^a	4.85
	LSD_{0.05}	0.43	0.29	0.46	0.34
Irrigation	Irrigated	10.38	9.22	72.90	4.96
	Non-irrigated	10.45	9.45	72.62	4.74
	LSD_{0.05}	0.28	0.30	0.35	0.25
Genotype (Hybrids)	Armagnac (FAO 490)	10.49	9.58 ^b	72.51 ^a	4.63
	Loupiac (FAO 380)	10.35	9.28 ^a	73.80 ^b	4.79
	Fornad (FAO 420)	10.41	9.21 ^a	72.29 ^a	4.94
	LSD_{0.05}	0.34	0.37	0.41	0.32
value with different letters in column differ significantly (LSD _{0.05})					

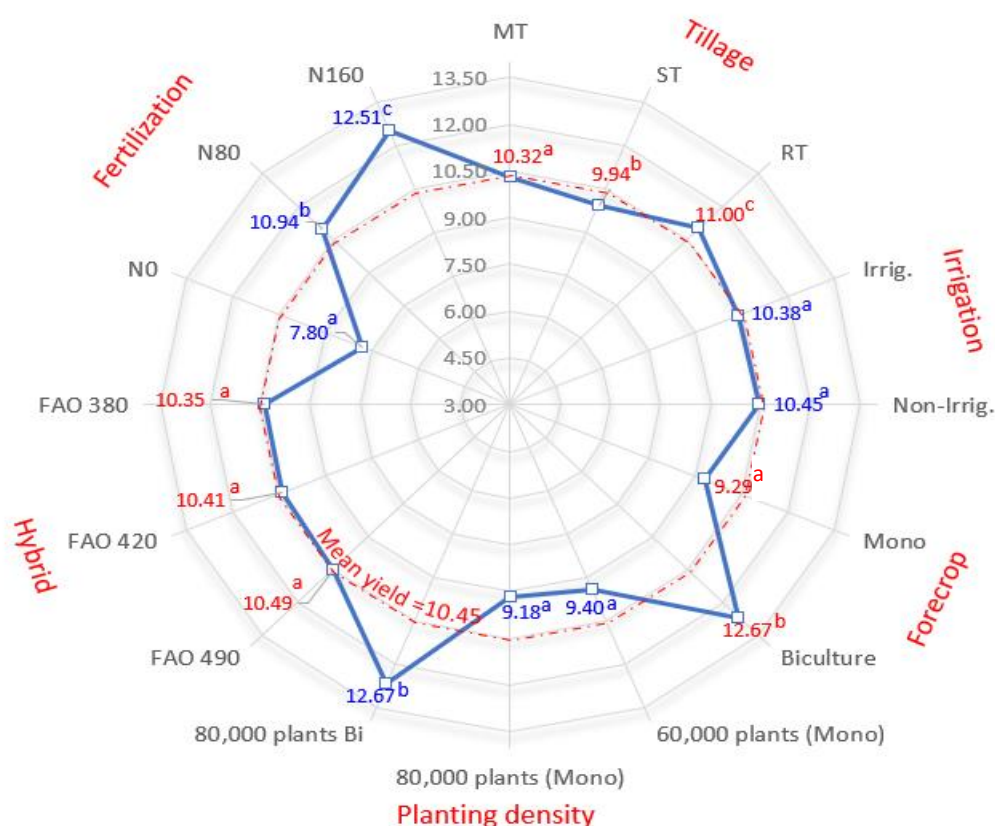


Figure 61. Radar chart summary of treatment effects on grain yield (t ha⁻¹) (Debrecen, 2018-2020)

Summary charts of treatment effects on grain protein, starch and oil content (%)

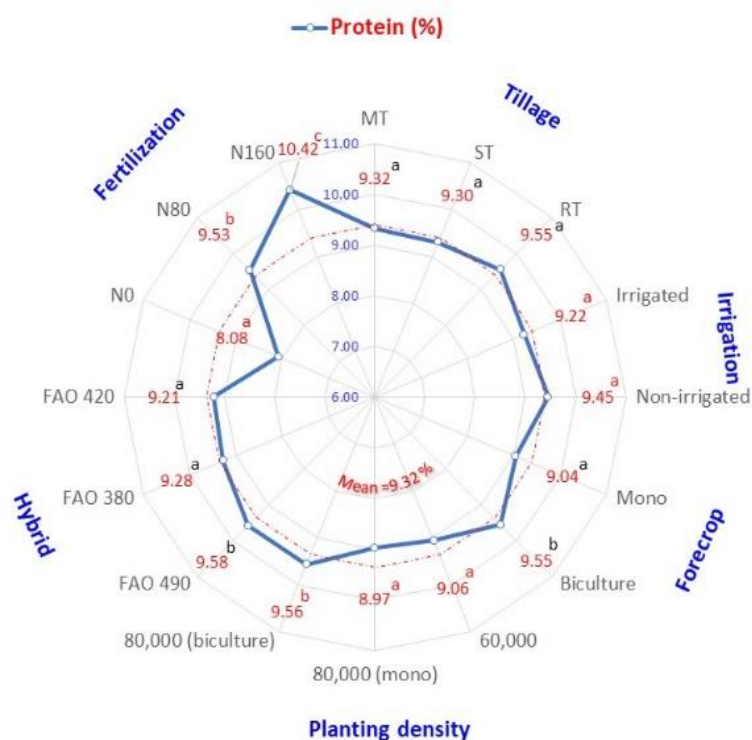


Figure 62a. Radar chart summary of treatment effects on grain protein content (Debrecen, 2018-2020)

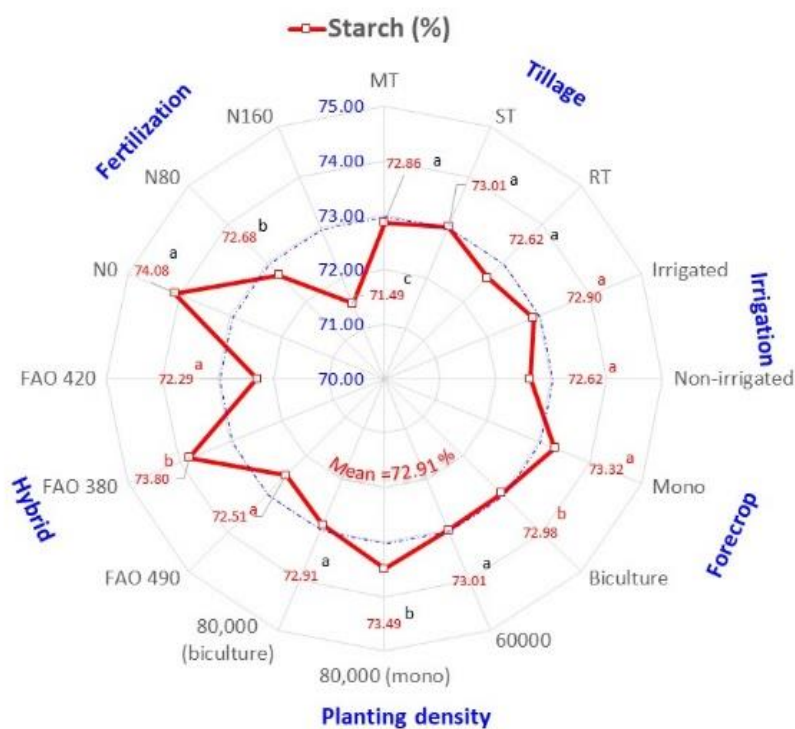


Figure 62b. Radar chart summary of treatment effect on grain starch content (Debrecen, 2018-2020)

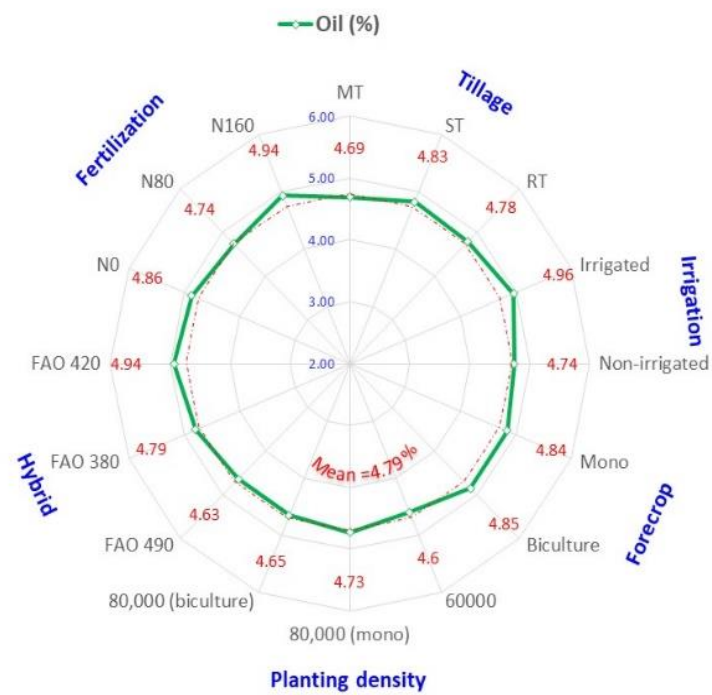


Figure 62c. Radar chart summary of treatments on grain oil content (Debrecen 2018-2020)

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Doctoral School: Kálmán Kerpely Doctoral School

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (3)

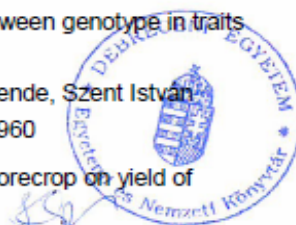
1. Bramdeo, K., Rátónyi, T.: Effect and interaction of crop management factors and crop year on the yield of maize (*Zea mays* L.).
Agrártud. Közl. 2, 31-41, 2020. ISSN: 1587-1282.
DOI: <http://dx.doi.org/10.34101/ACTAAGRAR/2/7406>
2. Bramdeo, K., Rátónyi, T.: Effect of tillage and fertiliser treatments on yield of maize (*Zea mays* L.) hybridss.
Columella. 7 (1), 57-65, 2020. ISSN: 2064-7816.
DOI: <http://dx.doi.org/10.18380/SZIE.COLUM.2020.7.1.57>
3. Bramdeo, K., Rátónyi, T.: Effect of tillage practices, fertilizer treatments and crop rotation on yield of maize (*Zea mays* L.) hybrids.
Agrártud. Közl. 2, 43-48, 2020. ISSN: 1587-1282.
DOI: <http://dx.doi.org/10.34101/ACTAAGRAR/2/3626>

Foreign language scientific articles in international journals (1)

4. Bramdeo, K., Rátónyi, T.: Yield response of maize hybrids to water supply, fertilization and planting density.
Adv. Biores. 12 (2), 108-115, 2021. ISSN: 0976-4585.
DOI: <http://dx.doi.org/10.15515/abr.0976-4585.12.2.108115>

Foreign language abstracts (4)

5. Mousavi, S. M. N., Bramdeo, K., Kith, K., Vad, A., Nagy, J.: Interaction between genotype in traits on FAO 340 hybrids based on GGE bi plot analysis.
In: 19th Alps-Adria Scientific Workshop : Abstract book. Ed.: Zoltán Kende, Szent István Egyetemi Kiadó Nonprofit Kft., Gödöllő, 24, 2020. ISBN: 9789632698960
6. Bramdeo, K., Rátónyi, T.: Interaction of tillage, fertilizer and winter wheat forecrop on yield of maize hybrids.
In: 19th Alps-Adria Scientific Workshop : Abstract book. Ed.: Zoltán Kende, Szent István Egyetemi Kiadó Nonprofit Kft., Gödöllő, 17, 2020. ISBN: 9789632698960





7. 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
8. Mohammed, S., Mousavi, S. M. N., Alsafadi, K., **Bramdeo, K.**: Tracking GHG emission from agricultural and energy sectors in the EU from 1990 to 2016.
In: Abstract book 18th Alps-Adria Scientific Workshop. Ed.: Zoltán Kende, Csaba Bálint, Viola Kunos, Szent István Egyetemi Kiadó Nonprofit Kft., Gödöllő, 24-25, 2019. ISBN: 9789632698182

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.

14 July, 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

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the signature of the candidate

DECLARATION

I certify that Bramdeo Karamchand; 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

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ACKNOWLEDGEMENT

A debt of gratitude is owed to all my professors, lecturers and in particular, my supervisor, Dr. Rátonyi Tamas. Thank you for your guidance and encouragement and for being part of my great experience at the University of Debrecen.

To my colleagues and everyone else I had the opportunity to interact with and who have contributed to my pleasant and memorable experience in Hungary, nagyon köszönöm szépen!