UNIVERSITY OF DEBRECEN
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AND ENVIROMENTAL MANAGEMENT
Institute of Land Use, Engineering and Precision Farming Technology

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Editor:
ADRIENN SZÉLES

Author:
JÁNOS NAGY
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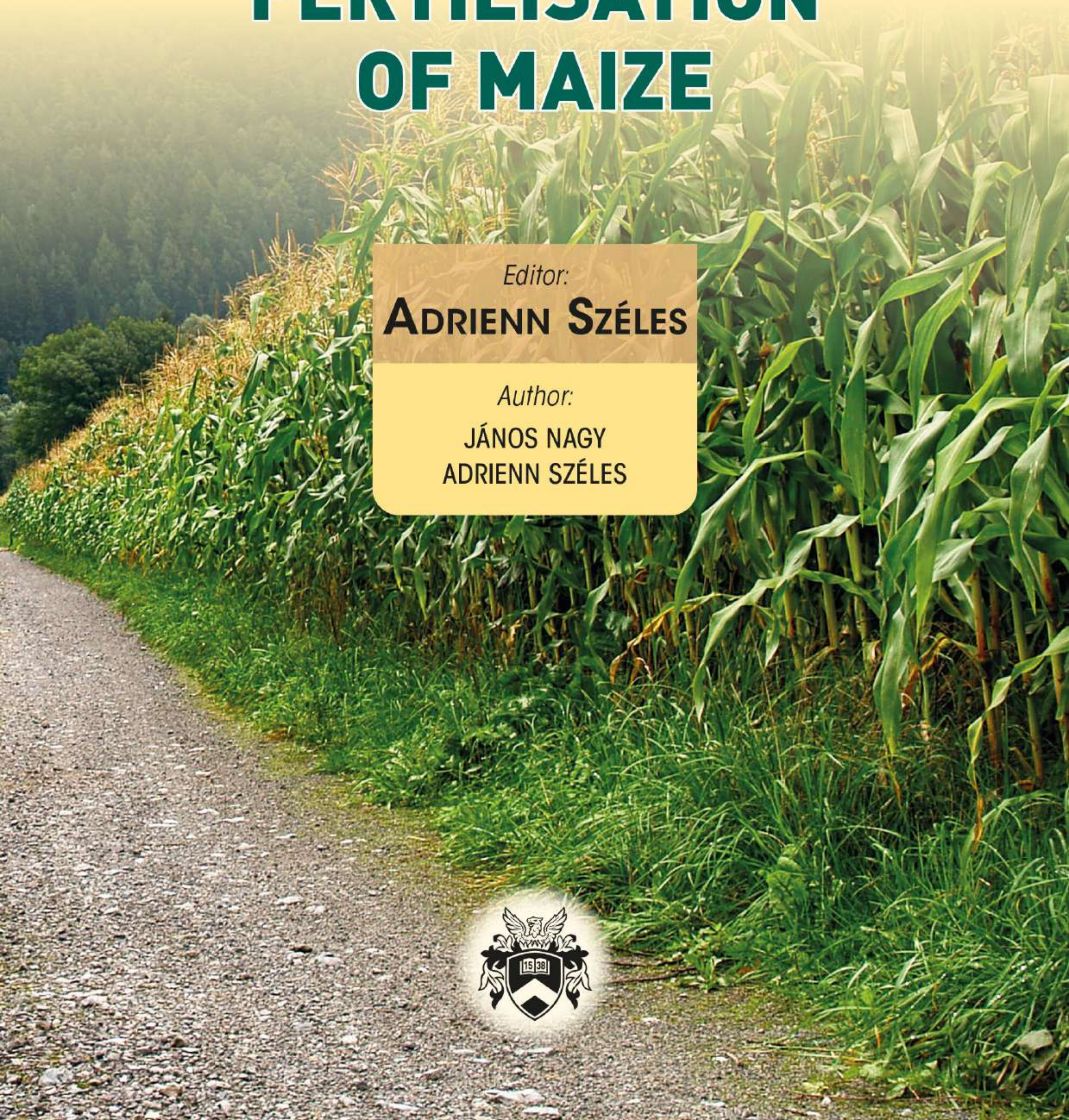

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ADRIENN SZÉLES

Fertilisation of maize

Academic lecture notes

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Author:
ADRIENN SZÉLES – JÁNOS NAGY

Editor:
ADRIENN SZÉLES

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Introduction

The purpose of fertilisation is to introduce organic and inorganic substances into the soil that maintain and improve the soil's composition, chemical and physical properties and biological condition, and have a positive effect on soil fertility and crop yields.

In Homer's (900–700 BC) heroic poem, The Odyssey, Xenophon (434–355 BC) in his „On Farming" and Theophras (372–287 BC) in his „History of Plants" already draw attention to the benefits of fertilising soils.

Liebig's (1861) classical nutrient supply theorem is that plants take up nutrients for their growth and development (life functions), which they extract from their environment – in a narrower sense, from the soil. The loss of nutrients must be compensated by fertilisation (*Debreczeni* 1979, *Buzás* 1983).

Fertilisers are substances that increase the fertility of the soil. *Direct fertilisers* (plant manures), which meet the nutrient needs of plants. *Indirect fertilisers* (manures), which mainly affect the physical and colloidal properties, structure and biology of the soil and their application (lime, gypsum, etc.) often falls under the heading of soil improvement.

In a narrower sense, only those substances that feed plants and the micro-organisms that live with them can be called fertilisers. On this basis, two groups of *fertilisers* can be distinguished: *organic fertilisers* are predominantly derived from agricultural production, with only small amounts coming from industrial and other plants (faecal matter, municipal waste, food waste, etc.), and *artificial fertilisers* (mineral fertilisers) are industrial products consisting of inorganic compounds.

Organic fertilisers include: livestock manure, slurry, green manure, straw manure, maize straw, legume stubble and root residues, compost, municipal solid waste, faecal matter, peat and poultry manure, and industrial organic waste.

Fertilisers are classified according to their active ingredient content and state of aggregation as follows: *Single-ingredient fertilisers* containing only one active ingredient (nitrogen, phosphorus, potassium or one of the trace elements). They may be used in solid or liquid form. *Multi-active fertilisers,* of which solid fertilisers can be divided into three groups. *Compound fertilisers,* a compound described by a formula, containing two nutrients in each molecule. A *compound fertiliser,* which contains several compounds and 2–3 or more nutrients, cannot be expressed by a formula. *Mixed fertiliser* is a mixture made in a factory or plant.

One of the most decisive factors in achieving a high average yield is adequate nutrient supply, intensive fertilisation. Maize is a crop with high nutrient requirements. It requires 25 kg N, 13 kg P O_{25} and 22 kg K_2 O for 1 tonne of grain and its vegetative part, so it is a high nitrogen demanding crop, while its phosphorus demand is medium and its potassium demand is high.

1. Organic fertilisation

The use of organic manure was significant before the 1960s, but decreased from the 1970s due to increasing fertiliser use. By 1993, the amount of organic manure used had decreased dramatically (70–75%) compared to the late 1980s (*Figure 1*). Between 2005 and 2008, the area of land used for organic manure increased by 7.5%, but from 2009 – except in 2016 – the amount of land used for fertiliser application increased by 7.5%. On average, 5.48% of the agricultural area was organically manured in 10 years (2009–2018) (6.23% of the area in 2009, 4.57% in 2018). At the same time, the amount of organic manure applied decreased, with an average of 5.42 million tonnes. The extremes were 2017 (4.7 million tonnes) and 2009 (6.8 million tonnes).

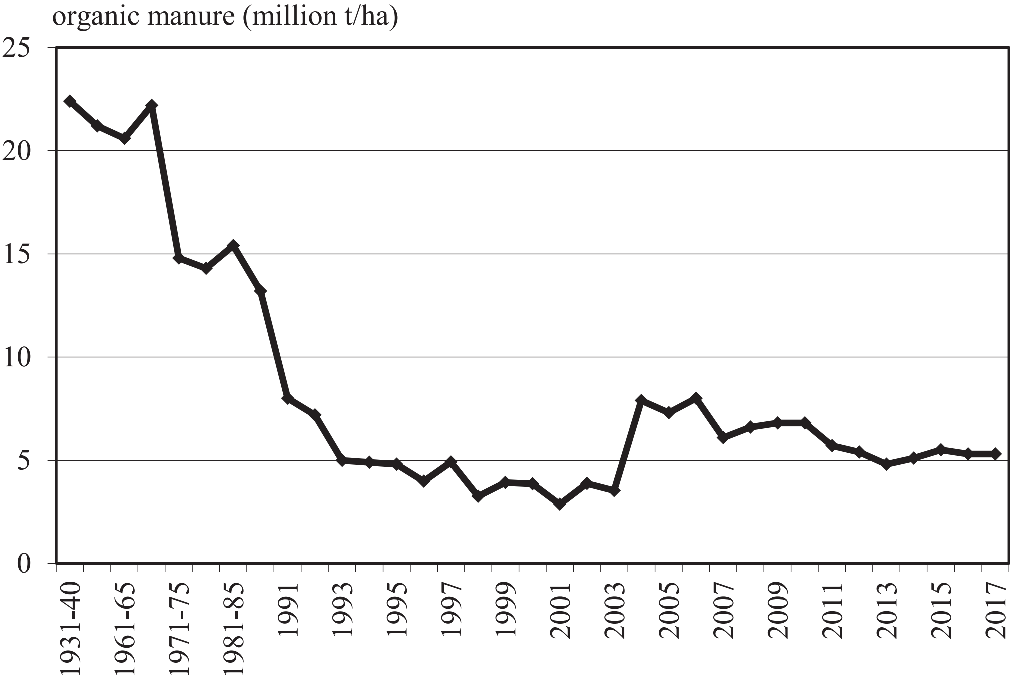


Figure 1. Organic manure consumption in Hungary, 1931–2018
(*based on HCSO data,* author's own construction 2019)

1.1. Manure application

Much of the literature on fertilisation attributes many other yield-enhancing effects to manure in addition to its nutrient effect. In addition to providing plant nutrients, manure contributes significantly to crop growth by improving the physical, chemical and biological properties of the soil.

The positive effect of manure is that it improves soil aeration, water holding capacity and water permeability (*Kalocsai et al.* 2007), while reducing soil compaction (*Papini et al.* 2011). Its beneficial buffering effect is well established in both acid and alkaline soils. In addition to NPK, manure also adds important microelements to the soil. Manure is an important source of carbon dioxide, and increased carbon dioxide content in the subsoil can increase the intensity of assimilation. Manure improves soil adsorption.

It has a beneficial effect on soil life, the soil enzyme system and the activity of certain enzymes, stimulates the activity of soil bacteria and other micro-organisms and reduces the risk of soil pest accumulation.

In 10 tonnes of well-treated manure, 50–60 kg N, 25–40 kg $P O_{25}$, 60–80 kg K_2 O are mostly in organic form, and therefore provide a continuous and lasting supply of nutrients to plants during their digestion (*Czuba* 1978, *Müller* 1990, Ábrahám 1980).

The mature manure has a C/N ratio of 20/1, is well spreadable and has the highest nutrient content. The changes in the composition of cattle manure during maturation are illustrated in *Table 1.*

Table 1. Changes in the composition of fresh cattle manure

Changes in the composition of fresh cattle manure					
Features	0	2	4	6	8
	after maturing for one month				
Humidity %	75.00	75.00	73.00	70.00	68.00
Ash %	4.00	6.00	8.00	12.00	15.00
Organic matter %	21.00	19.00	19.00	18.00	17.00
Total N%	0.40	0.45	0.52	0.58	0.65
NH_4 -N%	0.15	0.10	0.08	0.05	0,02
All P O $\%_{25}$	0.20	0.28	0.32	0.36	0.40
Total K O$\%_2$	0.50	0.65	0.70	0.79	0.86
Mass of manure (t)	100.00	67.00	58.00	50.00	45.00

Source: *Sarkadi* 1964

Depending on the maturation and storage period, the content values vary, according to which good-medium-weak categories can be formed. The value of the manure is determined by the content and consistency. The assessment of manure is based on the NPK content (*Table 2).*

Table 2. Evaluation of manure according to NPK content

Evaluation of manure according to the NPK content			
Features	Good	Medium	Weak
N %	0.50–0.80	0.40–0.50	0.30–0.40
P O $\%_{25}$	0.25–0.50	0.20–0.25	0.15–0.20
K O$\%_2$	0.60–0.80	0,50–0.60	0.30–0.50
Organic matter %	18.00–22.00	15.00–18.00	10.00–15.00
C:N ratio	15–20 : 1	20–25 : 1	20–30 : 1

Source: *Sarkadi* 1964

From a crop production point of view, the main question is whether, in addition to its nutrient effect, the use of stable manure will increase the quantity or improve the quality of the crop in a detectable way. It is advisable to spread out the application of NPK over 2 to 3 years, since the application of the nutrients in organic bonds is continuous (*Kismányoky* 2001). The utilisation of the manure is highest in the first year, when it is estimated at 40–60%. In the second and third years it decreases steadily to about 30–35% and 10–12% respectively. In the fourth year, there is no effect on sandy soils, but on high-plasticity soils it is 5–10% (*Kalocsai et al.* 2007). In monoculture experiments on spilled chernozem soils, the results of maize monoculture experiments show that there is no significant difference in the effect of manure and fertiliser even after 30 years (*Kudzin* and *Gupalo* 1959). In some farm experiments, the superiority of fertiliser with the same NPK active ingredient as the farmyard manure is still significant after 60 years (*Iversen* 1960).

Krámer (1979) investigated the effect of manure on N, P and K fertiliser effects in experiments on a slightly eroded forest residue chernozem soil containing 2.3% humus and 1–15% $CaCO_3$. The soil of the experiment was initially poorly supplied with phosphorus and moderately supplied with potassium. The fertiliser rates were 104 kg N, 61 kg P O_{25} and 69 kg K_2 O/ha/year. In the 35 t/ha/4 yr of manure, 62 kg N, 39 kg P O_{25} and 61 kg K_2 O/ha of nutrients were applied per year. In the maize-maize-winter wheat crop rotation, the manure was applied under the previous year's maize. Without the application of farmyard manure, the effect of N, P and K fertiliser was 1.2–0.7–0.6 t/ha in maize. The effects of the manure in years 1–2 were able to fully replace the effects of the PK and 50–60% of the effect of N.

Less is said about the micro-nutrient content of livestock manure, although it is the best means of micro-nutrient replenishment. Artificial products (sprays, chelates, granules, etc.) do not have the potential of stable manure. In mature manure, the major trace elements are Fe 1000–2000, Mn 50–150, Cu 2–15, Zn 2–10, B 3–17 mg/kg (*Kismányoky* 2001). The concentration of Cu, Zn and Cr in different manure types can vary between 8.4–1726, 39.5–11379 and 1.0–1602 mg/kg dry matter, depending on the species of livestock and the element content of the feed. Concentrations of Cu and Zn are highest in pig manure, followed by poultry and cattle manure (*Wang* 2013). Concentrations of other undesirable trace elements such as As, Cd, Hg and Pb are very low, less than 10 mg/kg (*Sager* 2007*, Wang* 2013). Regular organic manure application rarely requires targeted microelement fertilisation (*Zorn et al.* 2007).

In the long term, it is a key to maintaining soil fertility and achieving safe, high quality crops, but the soil protection and environmental function of manure cannot be underestimated (*Kismányoky* 2001).

1.2. Green manure application

Green manuring is a form of organic fertilisation where a crop is grown with the aim of applying its entire mass of fertiliser to the soil before flowering or budding.

The importance of green manuring was emphasised as early as the 2nd century BC by *Cato in his* book „De Agri Cultura" (On Agriculture), and in the 1st century BC by *Varro* in his „Rerum Rusticarum Libri Tries" (On Agriculture), and by *Virgil in his* „Georgica" and in the 1st century BC by *Pliny in his* „Naturalis Historia" (The History of Nature).

In 1929, Vilmos Westsik was the first to investigate the effects of straw, manure and green manure on soil fertility and structure in the sand crop rotation experiment he founded. In Hungary, green manuring was used exclusively on sandy soils for a long time. Only in the last decades has it spread to ploughed soils, mainly in irrigated arable land, sloping areas and even more so in large-scale orchards.

Green manuring is a one-sided nitrogen fertilisation (*Tisdale* and *Nelson* 1966)*, so it is advisable to apply phosphorus and potassium fertilisers at the same time to make it a complete fertilisation*. Green manuring increases the organic matter (humus) content of the soil (*Gyárfás* 1951, *Hofmann* 1991, *Yadav* and *Yaduvanshi* 2001). It improves the physical properties of the soil and increases its soil water retention and water holding capacity (*Andraski* and *Bundy* 2005, *Gyuricza* 2014), improves soil aeration, facilitates the cultivation of high-plasticity soils and improves soil structure (*Nagy* and *Seiwerth* 2005). In addition to its nitrogen effect, green manures also have a yield-enhancing effect, which depends on the amount of nitrogen collected and the green mass of the crop sown. The biomass yield and positive effect on soil fertility of green manure can be further increased by applying 50 kg N/ha under unfavourable site conditions (*Gyuricza* 2014, *Mikó et al.* 2012, 2015). When growing non-legume green manure crops, 30–40 kg N/ha should be applied before sowing. When sowing without applying N fertiliser, the seed is sown in a seedbed with a lot of undecomposed plant residues. Initial plant development is slowed down and even at sowing in late August, which is considered a better sowing time, a loss of 5–15 t/ha of green weight can be expected, depending on the crop species (*Gyuricza* 2008). Nitrogen application is recommended for second crop green manuring in all cases if possible, but definitely when leaving the straw of ear cereals in place (*Mikó et al.* 2016).

Green manure crops also play an important role in crop protection. They can be used in crop rotation to break the development cycle of certain pathogens and pests. Nematode control is mainly achieved by crucifers (*Nagy* 2002, 2005a, *Sanchez et al.* 2001), but phacelia has also been shown to be effective against the beet nematode (*Heterodera schachtii*) (*Inderjit* 2004). Nematode-resistant mustard and olive radish varieties inhibit the entire nematode development cycle (*Nagy* 2005b), thus freeing the soil for post-emergence growth. Studies with phacelia, mustard and olive radish have shown that cyanide compounds produced by their roots can cause significant nematode losses of up to 50–70%.

Green grasses also serve as habitats for beneficial organisms. They support earthworm activity, and worms accelerate the decomposition of plant residues (*Rämert et al.* 2000, *Sanchez et al.* 2001). Phacelia, mustard and olive radish have caused significant 50–70% larval mortality of the earthworm beetle (*Budai et al.* 2005). Green grasses also affect the development of beneficial and harmful fungi in the soil. They have a very good weed suppressive effect (*BlacHCSOaw et al.* 2001, *Mustafa* and *Potty* (2001), but the seeds of green herbs can be overgrown in the soil and later germinate and become weeds (*Roszik* 2003).

The greater uptake of green manure crops is hampered by the uncertainty of green mass, mainly due to lack of rainfall, and the high additional costs of sowing them (*Kismányoky* 1993, *Abawi* and *Widmer* 2000, *Labarta et al.* 2002), although the costs are less than 20% of the total cost of manure application (*Nagy* and *Seiwerth* 2005). Moreover, under unfavourable site conditions, a single application of green manure, despite the high amount of green biomass produced (30–60 t/ha), has no yield enhancing effect and a positive effect can only be achieved by repeated applications (*Gyuricza et al.* 2007, 2014, *Mikó* 2009, *Mikó et al.* 2011).

Green manure can be used with legume species (most commonly crimson clover, berseem clover, vetch species, lupin species, sainfoins species, broad beans, grass pea, brown hemp), cruciferous species (oil radish, white mustard, fodder rape) and other species (buckwheat, phacelia, sorghum, garden cress, green rye, black oats, black seed). Legumes add approximately the same amount of organic matter and nitrogen to the soil as 14 t/ha of manure. However, it cannot be considered as fully equivalent because the organic matter in green manure decomposes much more easily and therefore has a shorter duration of action in the soil. The nitrogen compounds decompose so quickly that ammonia and nitrate can be detected 8 days after ploughing. The ammonia and nitrate compounds, which are rapidly formed, are subsequently lost substantially through leaching and denitrification (*Nyiri* 1993). The yield-enhancing effect of legume green manures lasts for 3 years according to *Westsik* (1928).

Experiments and production experience with the use of legume green manures in Hungary and many other countries show that the use of legume green manures can significantly increase maize yields, but the seed requirement for legume green manures is usually high. *Cherr et al* (2006) demonstrated that legume green manure crops required little or no fertiliser application.

Green manuring with lathyrus resulted in an increase in maize yield, but similar increases were also observed with nitrogen fertilisation (*Győrffy et al.* 1965). The disadvantage of using vetch as a green manure is that it removes a significant amount of water from the soil, and maize yields are lower in the dry year after green manure with vetch than without green manure. In a suitable year, the rapidly available nitrogen provided by vetch was 90–180 kg/ha (*Sainju et al.* 2000), 135 kg/ha (*Sweeney* and *Moyer* 2004), 80 kg/ha (*Schomberg et al.* 2006). Most nitrogen was provided by vetch (299 kg/ha) and lupin (255 kg/ha) (*Figure 2*) (*Mikó* 2009). Nitrogen and phosphorus availability was enhanced by alfalfa, red clover, sweet yellow clover and common vetch (*Cavigelli* and *Thien* 2003, *Astier et al.* Oil radish provided the highest phosphorus and potassium uptake (105 and 293 kg/ha), while phacelia, mustard, phacelia-mustard-oilseed rape mixture and common vetch provided 80 kg/ha phosphorus and 293 kg/ha potassium (*Mikó* 2009).

Maize yields were significantly increased by common vetch (*Astier et* al. 2006), red clover, rapeseed and a mixture of the two (*Tejada et al.* 2008). Under unfavourable site conditions, single green manuring, despite the large amount of green biomass produced (30–60 t/ha), has no yield enhancing effect, and positive effects can only be achieved by repeated applications (*Mikó* 2009).

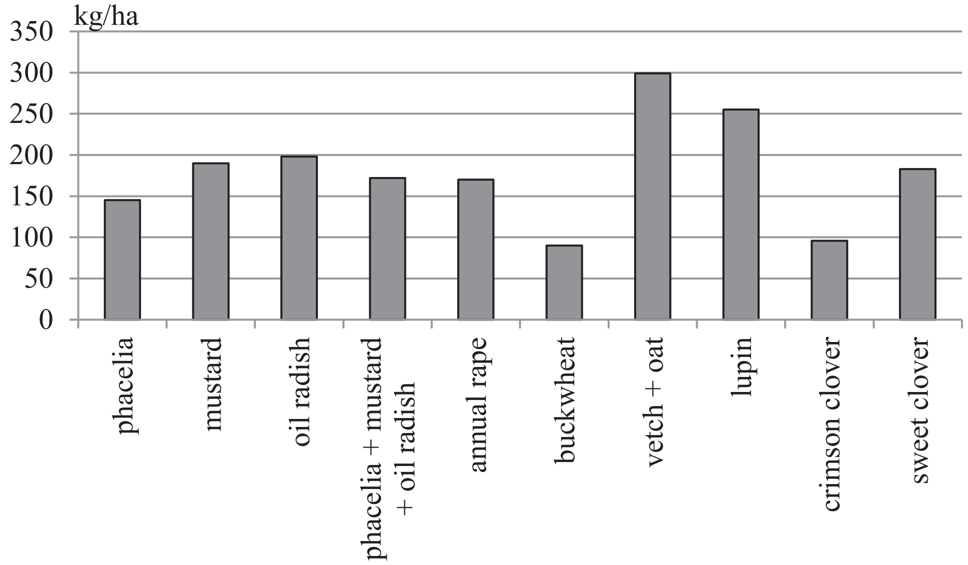


Figure 2. Average N uptake by green herbaceous crops (kg/ha)
(Source: *Mikó* 2009)

A prerequisite for a better use of green manure is to restore the nutrient balance. Otherwise, green manuring is ineffective, but may also reduce the yield of the successor crop (*Westsik* 1951, *Millar* 1955, *Győrffy* 1958, *Stikler et al.* 1959, *Bauer* 1973, *Antal* 1999).

In the European Union, a long and conscious effort to change attitudes has resulted in the current practice of mass production of green manure crops, which has been a priority for some time. The Ministry of Agriculture's „Best Farming Practice" proposes and demands new applications from producers in the cultivation of arable crops.

1.3. Other organic fertilisers

A timely harvested maize stalk has a significant feed value. In the farm trials, maize stover without nitrogen supplementation resulted in yield reductions. Nitrogen application could be used to compensate for the reduction, but 50–100 kg of nitrogen fertiliser per hectare were required to avoid the adverse effect (*Győrffy et al.* 1965). Maize stalks and roots are nitrogen-poor, and to make up the deficiency, the by-product estimated from the grain yield (1:1 grain/stalk ratio in dry matter) should be compensated for the high C/N ratio with a N fertiliser active ingredient at a rate of 1 kg N/100 kg dry matter. Organic fertilisation of fields far from the farm can be beneficial and can save on the cost of harvesting and transporting maize stover.

The role of stubble and root residues in soil fertility has long been recognised, but their impact on soil, quantity and quality have only recently begun to be studied in detail. Fertilisation also results in a higher mass and nutrient content of plant residues being deposited and retained in the soil. The advantage of the root system over the organic fertilisers applied to the soil is that it is homogeneously interwoven with the soil, so that the organic matter is distributed evenly. The nutrients that are released are constantly available to the plants. The dry matter content of maize root residues in the upper 20 cm of the soil is 2470 kg/ha (*Kemenesy* 1972).

The quality of the stubble and root residues varies greatly between legumes and non-legumes. The organic residues of the latter are nitrogen-poor, with a high C:N ratio of 75:1 for wheat, 45:1 for maize and 38:1 for sunflowers. The C:N ratio of the residual organic matter is 14:1 for alfalfa and 15:1 for sweet clover, better than the 20:1 ratio of well-fermented manure. The difference between the roots of young and stunted plants and between green-cut and mature harvested plants is not only quantitative but also in terms of content, with the young plants having significantly higher nitrogen, phosphorus and potassium contents. Organic residues from annual legume-flowered plants also have a beneficial effect. Their C:N ratio is higher than that of perennials, and is almost equal to that of well-treated manure. The C:N ratio is 22:1 for peas, 18:1 for spring vetch, 16:1 for grass pea and 20:1 for broad beans. Therefore, the fertilising effect of annual legumes *can be considered equivalent to that of half-dosage manure application (Nyiri* 1993).

Continuous application of organic manure for three decades increased pH in acidic soils, and integrated application of optimal doses of NPK and organic manure resulted in increased organic carbon (from 7.9 to 12.0 g/kg at baseline) and higher yields (*Verma et al.* 2012), and improved maize harvest performance (*Bekeko* 2014).

In treatments without organic fertiliser (NPK) on Ramann brown forest soils, soil humus content has significantly decreased by 0.720 g/kg over more than three decades (SD5%=0.612). If this trend continues, soil humus content will reach the minimum lower limit in a few decades and a significant decrease in yields can be assumed. Soil organic matter content increases slightly as a result of the manure + NPK treatments, but the extent of humus enrichment is within the significance level. For the combination of NPK+straw manure and green manure, the humus content of the soil at the start (1984) remained practically constant. Increasing N rates significantly increased grain yield of maize compared to the control, with maximum grain yield provided by the 210–280 kg/ha N fertiliser amendment. The positive effect of manure + NPK was 7% on average for N treatments, 20% for N0, and 3% and 10% for NPK + straw incorporation into the soil + green manure, respectively (*Kismányoky* 2018).

All possible methods of organic fertilisation are of paramount importance, but they should be applied where the best effect in soil improvement can be achieved.

2. Fertilisation with artificial fertilisers

2.1. Beginning and evolution of fertilisation

In the literature on maize fertilisation, there are very different levels of knowledge on fertiliser application. *Balás* (1888) stated in the last century that ‚maize will tolerate the most extensive fertilisation possible, and there is no reason to fear that very heavy fertilisation may cause trouble'. *Cserháti* (1905) made a similar point: ‚the more we fertilise the maize, the greater the yield'. When maize fertilisation experiments were first started (1955), it was generally believed that maize did not respond as well to fertilisers as other cereals. *Grábner* (1956) stated that ‚if you add manure to maize, then fertilisation is unnecessary'. On the contrary, *Győrffy* (1966), on the basis of several years of results, concluded that maize in good soil fertility does not respond so much to direct fertilisation than to the general level of nutrient supply to the soil. *Surányi* (1957), *Bauer* (1959), *Dezső* and *Martin* (1965) emphasised, as in the previous observation, that it is better to plan and manage fertilisation over several years in the context of the whole crop rotation. *Drimba* (1997), using stochastic dominance studies with databases from polyfactorial duration experiments in Debrecen, demonstrated the reliable yield-increasing effect of fertilisation under different conditions.

But finding the optimum fertiliser dose is one of the most difficult tasks. *In addition to the nutrient requirements of the maize, the nutrient supply capacity of the soil and the application of organic and artificial fertilisers in previous years, the nutrient conversion rate of the hybrid and its fertiliser response must be taken into account when determining the fertiliser dose for maize.* However, analysis of multi-factor interactions is essential. This is where reliable long-term fertilisation experiments, as results from live field experiments in laboratories, can really help.

In Kompolt, on chernozem-brown forest soil, no reliable yield differences were obtained in 1959 for $N_{35}P_{35}K_{35}$ kg/ha of fertiliser active ingredient or for fertiliser rates higher than this. In 1960, however, 140 kg/ha of nitrogen active ingredient applied alone resulted in significant differences, and in a drought year fertilisation caused significant yield depression. However, at Putnok, on soils with poorer nutrient supply, $N_{105}P_{75}K_{120}$ kg/ha compared to a lower N rate reliably increased maize yields in all years, but even here a higher N rate had no yield-increasing effect (*Krámer* and *Pekáry* 1962, *Pekáry* 1969).

In an experiment conducted by *Sarkadi* and *Bánó* (1962) on meadow chernozem soil in Martonvásár, no significant yield differences were obtained in 1956 as a result of $N_{64}P_{61}K_{153}$, in 1957 as a result of $N_{83}P_{42}K_{198}$, in 1958 as a result of $N_{73}P_{36}K_{118}$ kg/ha fertiliser compared to the unfertilised control. However, in 1959 $N_{82}P_{66}K_{139}$, in 1960 $N_{108}P_{115}K_{242}$ kg/ha gave reliable yield increases. The variety was changed during the experiment and the number of plants was increased, and these conditions should be taken into account when evaluating the results.

In a maize experiment at Martonvásáron with different growing areas, the application of $N_{54}P_{43}K_{52}$ and $N_{108}P_{43}K_{52}$ kg/ha of fertiliser in two of three years (1958, 1959, 1960) resulted in a significant grain yield increase in favour of the higher fertiliser rate, and only in the treatment with the smallest growing area. In the years 1965–1968, among the effects of two fertilisation levels – 130 NPK kg/ha and 195 NPK kg/ha – on average of tillage treatments, a reliable yield increase was observed only in 1966 (*Győrffy* 1962, 1969). In experiments on chernozem soil, however, a significant yield increase was observed when 130 NPK kg/ha of total fertiliser was applied compared to the unfertilised control, but further increases in fertiliser rate were not effective (*Dezső* 1966, *Káposzta* 1974).

Láng (1976) – similar to the findings of Dezső and Káposzta – based on the results of the 1968–1970 maize fertilisation experiments of the Unified National Fertilisation Experiment (OTK), found that in one of 9 experiments on chernozem soil, a clear increase in yield was observed in comparison to the unfertilised control crop as a result of fertilisation. In two cases there was no significant difference and in six cases there was a yield reduction. On the basis of the results of the OTK fertilisation experiments, *Bocz* (1976) states an average of 275–370 kg/ha, with an optimum of 220 to 440 kg/ha of mixed NPK fertiliser as the optimum fertiliser for soils in the Transdanubian region.

In Kompolt, on chernozem-brown forest soil, the ongoing trial on the effect of crop rotation since 1962 answers a number of current questions (*Pummer et al.* 1997). For maize monoculture, the upper limit of the nutrient dose can be set in the interval of one and a half to two times (175–234 kg/ha for a mixed NPK active ingredient of 218 kg/ha) based on the analysis of the nutrient yield function.

The correlations between field experiments in Debrecen and the effect of fertiliser application on yields were investigated by *Nagy* (1995) using a second-degree regression function. After calculating the regression equation, he carried out the derivation of the function and used it to determine the fertiliser dose and the yield maximum. During the four years (1991–1994), the maximum total yield was obtained at a dose of 172 kg N/ha. Such a fertiliser rate cannot be recommended under any circumstances, the last kg of N fertiliser in this case gave zero yield increase. At the maximum yield, the yield increase varied between 1.8 and 3.0 t/ha, and the average increase per kg N fertiliser was 12–17 kg/ha. Examining the slope of the second-order function, he found that starting from zero in the first part, at low nutrient levels, he obtained high yields. Thereafter, the slope of the function decreased and a broad plateau was observed around the yield maximum, with little change in the quantity of yield. The slope of the second-degree function is so moderate that at this stage, reducing the fertiliser rate at the yield maximum only slightly reduced yield. This means that even with a lower fertiliser rate, the yield was close to the maximum yield, and further fertilisation caused only a very small increase in yield. Knowing this is very important from a practical point of view. A good example is 1993, when the maximum yield of 9.553 t/ha was obtained with 175 kg N/ha fertiliser. Approaching the maximum yield of less than 500 kg/ha, 104 kg N per hectare was sufficient, providing a yield of 9.061 t/ha.

The marginal efficiency test shows how much the last kilogram of additional fertiliser applied results in an increase in grain yield. At the fertiliser dose required for maximum yield, the marginal efficiency is zero. The effectiveness of N fertilisation can be well characterised by its N efficiency. The difference between the N fertiliser applied (input) and the N content of the yield (output) shows the productivity of production, the positive and negative effects and the risk of environmental production (*Figure 3).*

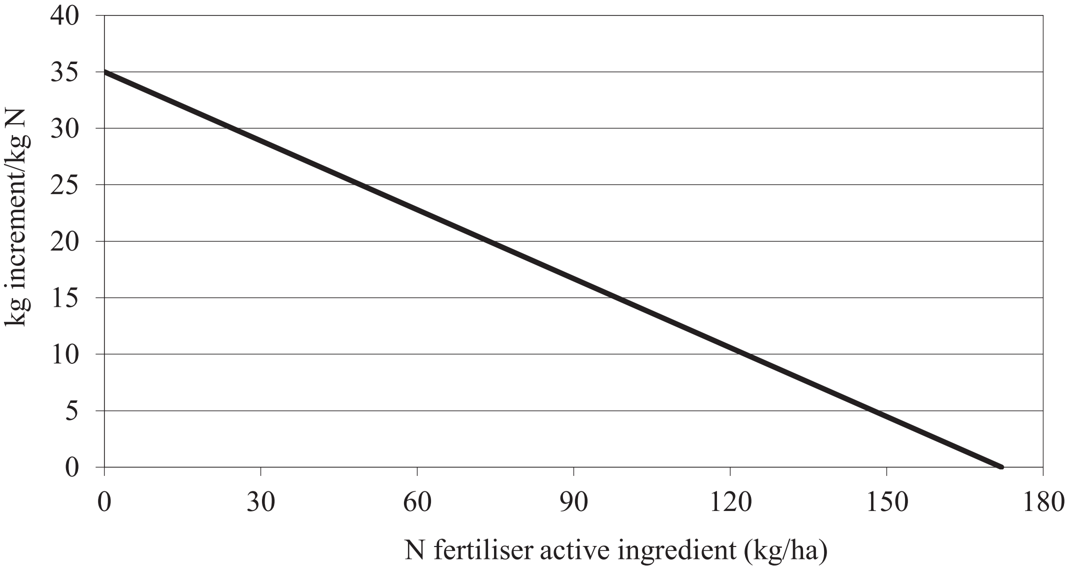


Figure 3. Efficiency of N fertilisation, Debrecen, 2019
(Source: *Nagy* 2012)

2.2. Fertiliser use in Hungary

Fertiliser use per agricultural area expressed in NPK was 6 kg/ha before the war, and even before the 1960s it was less than 30 kg/ha. The nutrient balance for the main nutrients (NPK) was negative in Hungary. This means that more nutrients were extracted by harvesting the respective crops than were released. Nutrient supply can no longer be based on manure alone, so the amount of fertiliser applied has steadily increased (*Dimény* 2005). Between 1960 and 75, fertiliser application reached 275 kg (*Figure 4*). This level of fertiliser use was typical until 1985. Between 1985 and 1990 there was a slight decrease, but from 1990 onwards there was a large decrease in fertiliser use. The yield of maize has decreased and fluctuated, of course due to the interaction of other technological elements. Active ingredient ratios have also changed. In the 1950s and 1960s, the proportions of nitrogen and phosphorus used were the same, but later nitrogen use became more important (*Loch* 1999b, *Nagy* 2021).

Over the last twenty years (2000–2019), fertiliser use has fluctuated significantly, with an average of 477 thousand tonnes/year of active substances. Consumption increased steadily from 2000 and then fell by 28% between 2007 and 2009. The application of phosphorus and potassium halved during this period. From 2010 onwards, the application increased again. The peak year was 2017, with 659 thousand tonnes used (424 thousand tonnes of nitrogen, 118 thousand tonnes of phosphorus and 116 thousand tonnes of potassium) (*Figure 5*). Fertiliser use per hectare almost doubled in 20 years, from 61 kg to 118 kg.

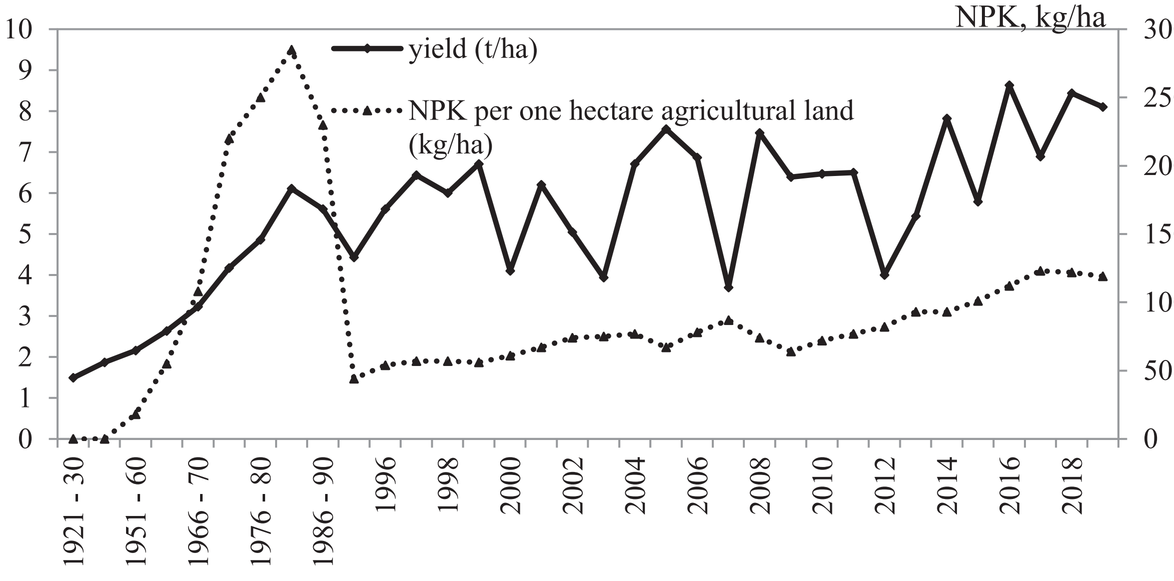


Figure 4. Fertiliser use and maize yields in Hungary, 1921–2019 (*HCSO data based on* author's own construction 2020)

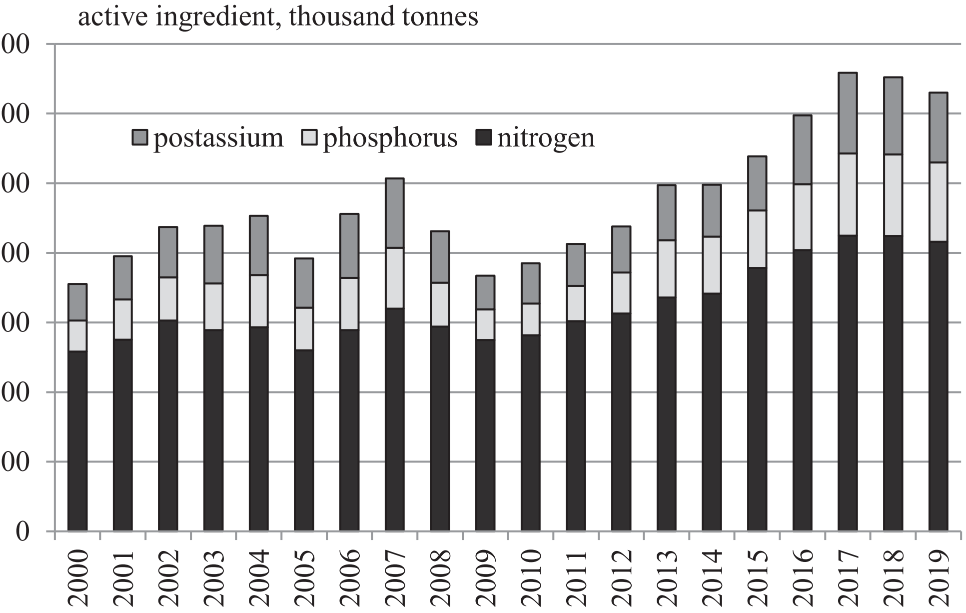


Figure 5. Nitrogen, phosphorus and potassium fertiliser use in Hungary, 2000–2019 (*based on HCSO data,* own ed. 2020)

2.3. Nitrogen fertilisation

The N content of soils is an important factor in soil fertility (*Nyiri* 1993). The total N content of soils can vary between 0.02–0.4%. In the cultivated layer, more than 95% of the total N is present in organic bonds and the amount is proportional to the humus content. Plants can utilise inorganic forms of NO_3 and NH_4 , which represent only a fraction of the total N content of the soil. It can also take up organic compounds, e.g. N in amino acids and urea. Most of the nitrogen is taken up by the roots, but can also be taken up by the leaves. N taken up in inorganic form is rapidly converted to organic N compounds. N from the atmosphere also plays an important role in the N supply of plants. Nitrogen in the air cannot be used directly by plants, but is only available through micro-organisms. Nitrogen is in a constant cycle in nature.

Some processes of nitrogen cycling enrich the soil in N, while other processes result in a loss of N (*Figure 6*). Soil enrichment processes are fertilisation, organic fertilisation and N fixation by micro-organisms. In addition to N uptake by plants, denitrification and N leaching are sources of loss. Ammonification and nitrification, which convert organic compounds into soluble N compounds, play an important role in plant nutrient supply (*Loch* 1999b, *Nagy* 2012).

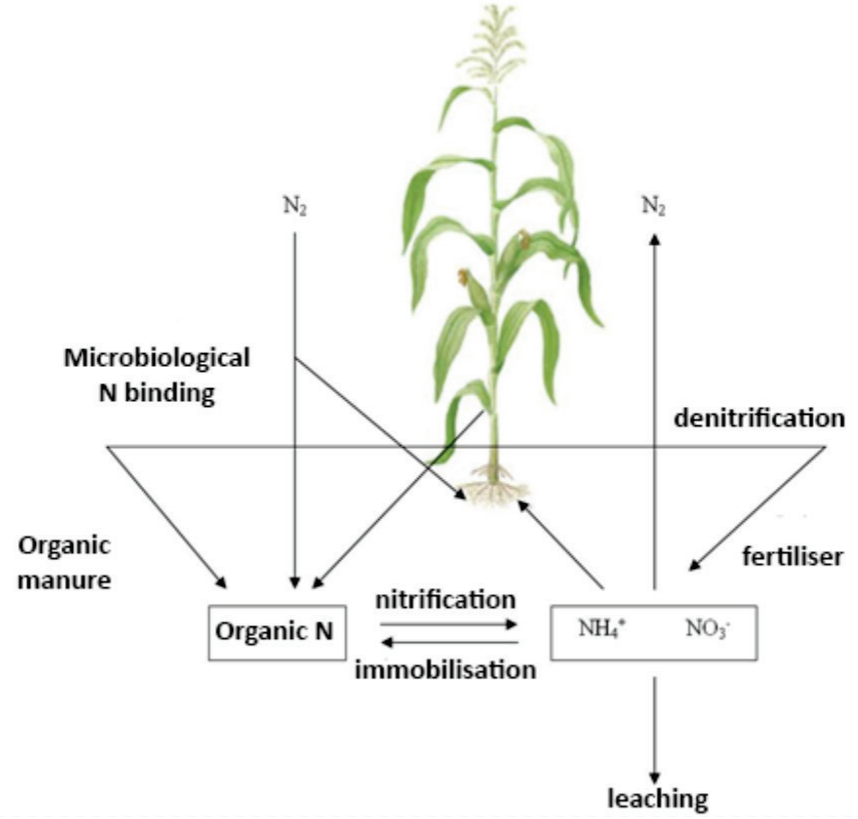


Figure 6. The nitrogen cycle
(Source: *Loch* 1999b)

The movement of N compounds in the plant is undisturbed, which is why N deficiency is mainly observed in older leaves, where N migrates to younger green parts in case of N deficiency (*photo 1.1*). Chlorophyll content of N-deficient plants decreases, meristem function slows down and the resulting cells age prematurely. Older leaves turn yellow, which may be accompanied by a reddish, anthocyanin discolouration.

The amount of N supply is the most important determinant of crop yield (*Bocz* 1976). N applied at optimal rates improves quality (*Izsáki* 2009, *Hegyi et al.* 2008, *Széles et al.* 2018b) and affects the uptake of other elements (*Bruns* and *Ebelhar* 2006). In the case of N deficiency, dry matter accumulation in maize plants is lower and the dynamics of dry matter accumulation are slow (*Győrffy* 1965, *Hanway* and *Russell* 1969, *Debreczeniné* and *Szlovák* 1985, *Berzsenyi* 1993ab). Excessive or unilateral N nutrition can cause a number of risks and damage. Excessive N in excess of the required amount causes yield depression and harmful nitrate accumulation. NO_3-N accumulating in the soil can leach out and pollute the environment. Plants with excessive N are prone to lodging, increased susceptibility to disease. If N is in relative excess compared to other nutrients, the same adverse effects occur as in the case of overfertilisation.

The effect of N has been investigated in maize experiments at several locations (I. Chernozem soils, II. Brown forest soils, III. High-plasticity meadow soils, IV. Low-plasticity sandy soils and V. Saline soils). The N dose required for the most economical yield varies in each location. An average of 190 kg N/ha applied to low-plasticity sandy soils to ensure economic yields is already environmentally damaging on soils susceptible to nitrate leaching (*Németh* and *Kádár* 1999).

Csathó (2004), after synthesising the results of the Hungarian field N fertilisation trials, concluded that the average N fertiliser application of about 50–70 kg/ha applied to arable land in the last 10–15 years does not provide the maximum nitrogen demand of N-demanding crops for economic production, taking into account the decreasing N supply of Hungarian soils and the modest application of organic fertiliser due to the low animal density in Hungary.

2.4. Phosphate fertilisation

Phosphorus occurs in soil in both organic and inorganic forms. The total phosphorus content of soils varies between 0.01 and 0.12% P (*Győri* 1984, *Loch* 1992). The results of a field experiment conducted by *Singh et al.* (2019) between 2009 and 2015 showed that applications of P above 59 kg/ha bring soils with low and medium tests (measured by the Mehlich-1 method) to high soil P levels.

For plants, phosphorus is the only element whose compounds are involved in almost all metabolic processes. It is found in plants in both inorganic and organic forms, but the most important role is played by organically bound phosphorus. The most important are nucleic acids, which are involved in the most important processes of life activity, protein synthesis, growth and division, and the transmission of hereditary traits. Like nitrogen, phosphorus is safely stored in plants and reused later in development, being reallocated to other organs (from leaves to seeds) depending on the phosphorus requirements of organic matter synthesis. Phosphorus is concentrated in the part of plants that is removed from the farm, in whole or in part, as feed or food. This should be taken into account when calculating and supplying the phosphorus needs of plants.

Phosphorus is closely related to nitrogen and protein compounds. Generative organs have 3–6 times more phosphorus than vegetative organs. An adequate supply of phosphorus accelerates plant development and maturation (*Nagy* 1993).

Field crops take up only about 5–10% of the P applied with fertiliser in the first year (*Greenwood et al.* 1980). Often 90% of the plant P uptake comes from the so-called „residual" P in the soil, i.e. freshly applied P cannot compensate for low soil P supply (*Johnston et al.* 1986).

The P requirement of maize is not high, but the P fertiliser response is poor. In an average of 84 domestic field P-effect experiments, *Csathó* (2004) found that the P_2O_5 dose required for economic maize production was 22 kg/ha, grain yield of P control plots was 6.26 t/ha, yield without P fertilisation was 95%, and the P effect in terms of yield surplus was 0.25 t/ha, which is very modest.

Zhang et al. (2015) used a 30-year database of 419 farms to evaluate the response of maize yield to P treatments (control [P0], recommended P rate based on 5 years of soil test results [RPR], 50% of RPR [50%RPR], 150% of RPR [150%RPR]). The average RPR yield was 9.9 t/ha. 150%RPR did not increase yield. A relative reduction in P (50% RPR) resulted in a yield loss of 4%, confirming that RPR was within the correct range (*Figure 7*).

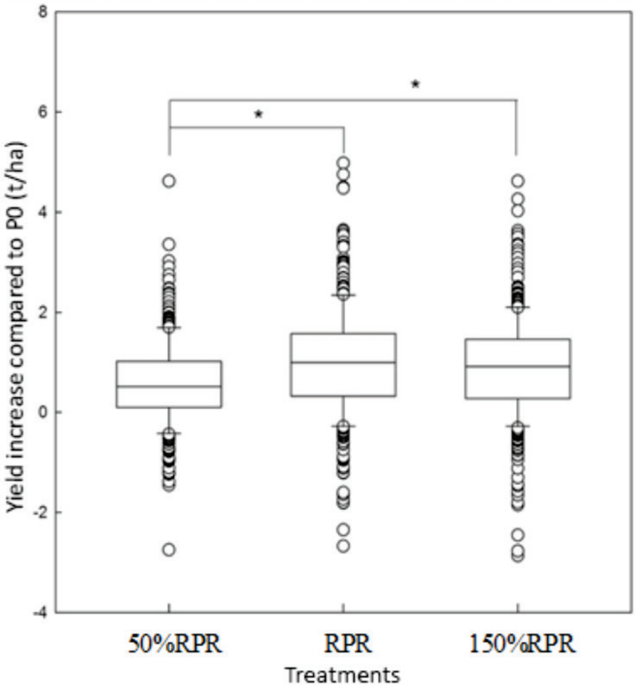


Figure.7. Yield increases above control, averaged over 419 experimental sites and years
(Source: *Zhang et al.* 2015)

In an experiment with 16-year-old maize, P treatments reduced mycorrhizal spore counts and mycorrhizal colonisation of maize roots (*Ortas* and *Islam* 2018). P deficiency inhibited root elongation while inducing lateral root proliferation (*Péret et al.* 2014). The optimal and economical P fertiliser rates under the given agroecological conditions were 100 kg/ha (*Masood et al.* 2011) and 120 kg/ha (*Khan et al.* 2014), which increased maize plant height, stem diameter and yield.

A general metabolic disturbance in the absence of phosphorus slows down protein and sugar synthesis, and starch synthesis is impaired. Phosphorus deficiency leads to a deterioration in the water balance of the plant and reddish discolouration, yellowing of the lower, older leaves and eventually lodging (*Photo 1.2*). Insufficient phosphorus supply also results in delayed flowering and ripening. Over-application of phosphorus can lead to significant nutrient deficiencies. Excessive amounts reduce the bioavailability of Zn, Fe and other essential nutrients (*Zhang et al.* 2017, *Bindraban et al.* 2020).

2.5. Potassium fertilisation

Potassium is the seventh most abundant element in the earth's crust. Potassium is found in relatively high amounts in most soils, but only a small fraction of it is taken up by plants. The total potassium content of soils exceeds phosphorus and nitrogen in most cases. A constant process of transformation takes place in the soil, with insoluble K compounds becoming more soluble compounds. It has been shown that plants often extract more potassium with the crop than the soluble and exchangeable K content of the soil water.

Potassium is present as inorganic ions in plant cell fluids and colloids. Potassium is found in plants, most abundantly in young tissues, where metabolism and cell division take place. Most of it (80–90%) accumulates in the vegetative parts and is naturally returned with plant residues or does not leave the place of cultivation.

The importance of potassium in the life of a plant is manifold. As a plant macronutrient, it has a structuring and activating effect on enzymes, a role in photosynthesis, respiration, protein synthesis, carbohydrate formation and lipid synthesis (*Loch* and *Nosticzius* 1983, *Beringer* and *Nothdurft* 1985, *Weber* 1985, *Csathó* 1997). It increases the active uptake of water by plants and reduces evaporation. A balanced supply of potassium protects the plant from drought stress. Potassium increases plant resistance to disease and cold (*Huber* and *Arny* 1985, *Kádár* 1992). Its deficiency is often not immediately visible in the crop, but can lead to significant yield losses (*Kalocsai et al.* 2004a). Insufficient potassium supply to plants leads to a reduction in their resistance and a disproportionate increase in their evapotranspiration, which results in wilting and dieback of leaf tips and leaf edges (*Photo 1.3*). In case of overdosage, salt damage symptoms occur, with stronger green colouring of plant parts, shortening of the internodal spaces, reduced growth rate and increased generative character of the plants.

The biological cycle for potassium starts with the uptake of nutrients by plants (*Figure 8*). Potassium fertilisers are best applied with autumn tillage, as this will bring the fertiliser into the moist layer with abundant root growth. Increasing N and P fertilisation can lead to potassium deficiency. On more compacted soils, it is effective to provide K requirements 2–3 years in advance, together with phosphorus. However, higher K application may lead to temporary deficiencies of plant Ca and soil acidification (*Krisztián et al.* 1989).

Csathó's (2004) evaluation of a field maize K-effect experiment shows that the K dose required for maximum economic maize yield was highest in the AL–K_2O range below 120 mg/kg (100–130 kg/ha K_2O), which was halved (to 60 kg/ha K_2O) in the range between 120 and 160 mg/kg AL–K_2O, and reduced to one third (to 40 kg/ha K_2O) between 160 and 200 mg/kg AL–K_2O. On soils with AL–K_2O contents above 200 mg/kg, even in K-requiring maize, no K effects were obtained, and full yields were obtained without K fertilisation. Grain yield surpluses were significantly reduced with improved K supply: 2.4 t/ha in the range 41 to 80 mg/kg AL–K_2O, 0.7 t/ha in the range 81 to 120 mg/kg, 0.5 t/ha in the range 120 to 160 mg/kg AL–K_2O, and no yield increase with fertilisation were recorded in the range above 200 mg/kg. In maize, without K fertilisation, a full yield of 71% was obtained on humic sandy soils, 88% on sandy loam, 93% on loam, 97% on clay loam and 100% on clay soils. Potassium fertilisation resulted in a yield increase of 1.9 t/ha on deep humic sandy soils, 0.7 t/ha on sandy loam, 0.4 t/ha on loam and 0.2 t/ha on clay loam, while K fertilisation had no yield increasing effect on clay soils.

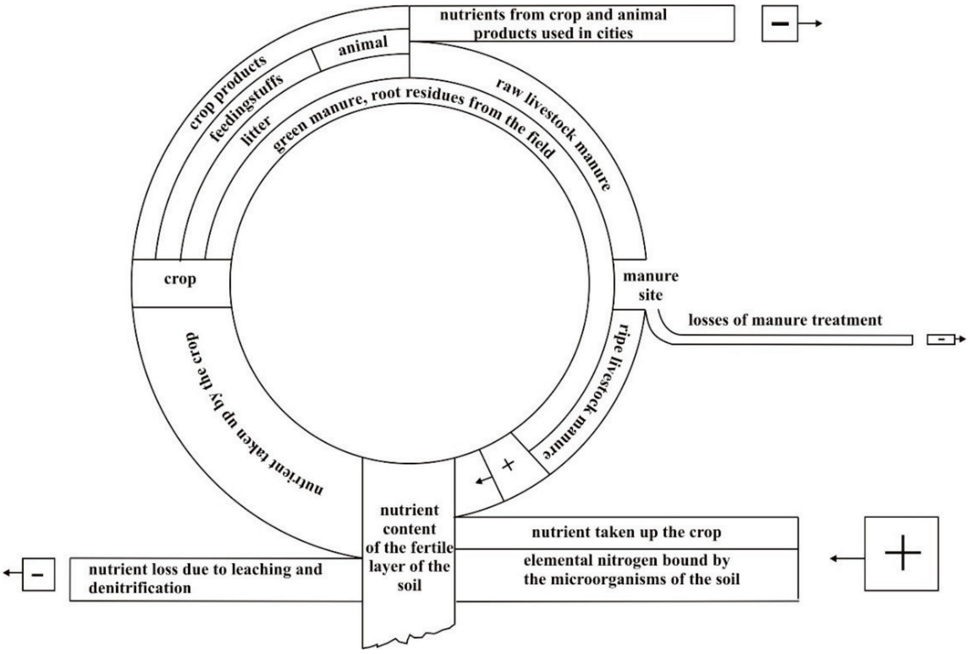


Figure 8. Crop nutrient cycling on the farm
(Source: *Di Gléria* 1958)

2.6. Calcium fertilisation

Calcium is present in the soil as soluble, exchangeable and reserve compounds. Water-soluble compounds are calcium chloride, calcium nitrate, calcium sulphate and, in carbonate soils, calcium bicarbonate. Calcium accounts for 75–85% of the exchangeable base content of temperate soils, with the highest exchangeable calcium content in the ploughed layer, 200–1000 kg/ha. This high amount balances the very low dissolved calcium content of the soil solution. As soil pH decreases, the amount of exchangeable calcium (and other basic cations) in the soil decreases, and as pH increases, the amount of exchangeable calcium increases. If very much calcium is present, $CaCO_3$ can precipitate and buffer the soil pH. In carbonate soils, calcium supply to plants is abundant due to the dissolution of carbonates. Calcium deficiencies occur mainly in unsaturated soils at pH<5 (*Debreczeniné* 1964, *Loch* and *Nosticzius* 1983, *Stefanovits et al.* 1999). Calcium helps to maintain chemical balance in the soil, reduces soil salinity and improves soil water balance. Soils with adequate amounts of calcium have better water infiltration properties due to calcium-sodium exchange. With the right irrigation, calcium can improve soil quality. Soils that are high in sodium and low in calcium do not allow water penetration. In these cases, gypsum or calcium carbonate may need to be applied depending on other soil chemistry factors (*Pónya* 2017). Smaller lime rates (0.5–2 t/ha active ingredient) are recommended to reduce calcium deficiency and reduce soil acidity, but significantly higher lime rates (usually 5–20 t/ha) are recommended for chemical soil amendments. Soil improvement should only be carried out on the basis of a plan prepared by a soil expert on the basis of laboratory test results (*Szakál et al.* 2006).

Plants take up calcium in the form of Ca^{2+}. The uptake of Ca^{2+} can be reduced by other metal cations and ammonium ions. The dry matter calcium content of plants is usually less than 1%. Exceptions are dicots, in which the calcium content is 1–3%. Calcium occurs in the plant either free or bound to plasma colloids. It is also found in the form of salts such as calcium phosphate, calcium carbonate, calcium oxalate, calcium pectinate and the calcium magnesium salt of inositol hexaphosphoric acid (phytin) (*Loch* and *Nosticzius* 1983).

Calcium plays a versatile role in the life of plants. It plays an important role in the formation and maintenance of the overall cell wall structure, nutrient transport through the cell membrane, nutrient uptake, protection against aluminium and manganese toxicity, root development, regulation of certain enzyme systems and nutrient balance in plant tissues. It is involved in the process of cell elongation and division and in the development of the cell's mechanical resistance, and through this, in the protection against insects and fungi. Adequate calcium content in the plant significantly enhances disease resistance, improves tissue tensile strength, heat tolerance and resistance to stress (*White* and *Broadley* 2003*, Kalocsai* 2006, *Szakál et al.* 2006, *Pónya* 2017).

In the plant, calcium migrates in the xylem in an acropetal direction. The amount transported is determined by the rate of transspiration. Calcium is hardly migrated back from the leaves to other organs, so there is a high accumulation of calcium in the leaves. This explains why, in most cases, older leaves have a higher calcium content than young leaves and why leaves have a higher calcium content than stem parts (*Kádár* 1992). Since calcium is hardly mobile in the plant, calcium nutrition is critical during dynamic developmental stages, but is important in maintaining a proper plant health status throughout the life of the plant. Adequate calcium levels in the plant population are most effectively achieved through soil nutrient replenishment. When applied through foliar application, the developmental stage of the plant is an important consideration (*Pónya* 2017).

Maize has a high calcium (CaO) requirement of 8 kg/t (*Antal* 2000). Some of the calcium removed by the crop can be replaced by superphosphate or ammonium nitrate of lime *(Filep* 1988). In the case of calcium deficiency, the roots do not grow, the growing tip becomes slimy, brown and then dies. The vegetative cone of the shoot is also damaged. Leaf edges are ragged as the edges of new leaves are crushed. In severe deficiency, leaves do not fully emerge. Due to the destruction of the vascular tissues of the lower shoots, the plants wilt easily even when well watered (*Photo 1.4*). Absolute and relative deficiency in plants occurs even in calcareous soils, where in principle the potential for uptake is given, but in many cases plants are not calcium deficient even in significantly acid soils. Its uptake may depend to a large extent on the potassium and magnesium ratio and on water deficiency (*Szakál et al.* 2006).

Calcium overdosage is rare and is not a direct problem, but is related to an upset in nutrient ratios, nutrient antagonism.

2.7. Magnesium fertilisation

The amount of water-soluble and exchangeable magnesium in the soil is the most important for plant nutrition. Expressed as a percentage of the S value, magnesium is about 5–25%. The magnesium content of the soil solution is determined by the exchangeable and the soluble or mobilisable stocks together. The water soluble compounds of magnesium are chlorides, sulphates and nitrates. Magnesium bicarbonate is also formed in dolomitic soils. The amount of magnesium that can be directly utilised is closely related to the soil properties and the formation conditions of the soils *(Darab and Reményi 1978,* *Loch* and *Nosticzius* 1983, *Fazekas et al.* 1992). The amount of exchangeable magnesium increases with the colloid content, so that in general the higher the clay and humus content of the soil, the more exchangeable magnesium it contains. The easily soluble magnesium content of soils depends on the degree of leaching. For this reason, acidic soils that are leached and poor in colloidal soils have the lowest levels of easily soluble and exchangeable magnesium. Most magnesium is present in the soil in the form of silicates and carbonates. The most important magnesium-bearing silicates are biotite, serpentine and olivine, and of the clay minerals chlorite and vermiculite *(Loch* and *Nosticzius* 1983, *Stefanovits* 1992).

The plant takes up magnesium in the form of Mg^{2+}. The uptake of magnesium may also be affected by antagonism between metal cations and the inhibitory effect of the ammonium ion. Magnesium uptake may also be inhibited by acidic chemistry *(Loch* and *Nosticzius* 1983) and the highly mobile nature of Mg^{2+} ion may leach from the root zone due to precipitation (*Mengel* 1976, *Grzebise* 2011, *Gransee* and *Führs* 2013), reducing nutrient uptake efficiency and yield.

Magnesium, as a constituent of chlorophyll, plays an important role in assimilation processes. Magnesium is involved in the biosynthesis of amino acids and proteins, in energy metabolism, and has a catalytic role in the functioning of enzymes (*Loch* 1970, *Loch* and *Nosticzius* 1983, *Cakmak* and *Kirkby* 2008, *Maathuis* 2009, *Hermans et al.* 2013). It plays an important role in maintaining cation balance. The magnesium content of plants is generally less than 0.5% in dry matter. Magnesium contents below 0.2% indicate magnesium deficiency. About 15–20% of the total magnesium is found in chlorophyll, but most of it is in ionic form and in chelate bonds. Some is found in salts (e.g. magnesium oxalate, phytin). Seeds accumulate relatively high amounts of magnesium (*White* and *Broadley* 2009), but this magnesium content has been decreasing significantly in recent times (*Verbruggen* and *Hermans* 2013, *Guo et al.* 2016).

Keeping the magnesium content of agricultural products within the right range is very important for human health (*Nèjia et al.* 2016). The magnesium requirement of maize is 50–70 kg/ha. Magnesium deficiency has a negative impact on root growth (shorter roots), assimilating and synthesising activities of plants. Plant growth slows down, becomes more susceptible to diseases and has a negative impact on yield and quality (*Brady et al.* 2005, *Hermans et al.* 2010). Magnesium deficiency is mainly found in older leaves, but unlike nitrogen or potassium deficiency, it is rarely found in the lowest leaves, but rather in the leaves around the mid- to lower two-thirds of the stem, and then migrates to younger leaves (*Terbe* 2017). Reduced chlorophyll formation results in chlorosis and yellowing of the plant. Maize leaves are characterised by striping and reduced fertility (*Photo 1.5ab*).

Excess magnesium is rarely found. Ca- and/or K-deficiency symptoms may occur as a result of cation imbalance.

2.8. Sulphur fertilisation

Sulphur is found in the soil in organic and inorganic compounds. The organic sulphur content increases with the humus content: about 50% of the total sulphur content in podzolic soils and 75% in chernozem soils. In wetland soils, it may be more. The inorganic sulphur content consists of sulphates and sulphides. The most important sulphates are gypsum ($CaSO_4$ -$2H_2O$) and anhydrite ($CaSO_4$), while Na_2SO_4 and $MgSO_4$ may also occur in saline soils. Sulphides: FeS_2 and FeS, which have a significant leaching hazard. The mineralisation of organic matter plays a major role in the sulphur balance of soils (*Loch* and *Nosticzius* 1983, *Terbe* 2018).

Plants take up sulphur as a sulphate ion. A significant proportion of the sulphate is reduced in the plant, forming SH groups, and is returned to the soil in this form in organic fertilisers and root residues. The sulphur cycle is similar to the nitrogen cycle. In the plant, the sulphate and nitrate ions are reduced and in the soil the reduced forms are oxidised. Under unfavourable conditions, the sulphur cycle can be disturbed. For example, sulphate may be reduced to hydrogen sulphide in unaerated, silt-laden soil. This is undesirable, firstly because hydrogen sulphide is toxic to plants, and secondly because hydrogen sulphide forms iron sulphides insoluble in iron, so that the uptake of sulphur and iron is inhibited. The formation of metal sulphides can also result in deficiencies of other trace elements (*Loch* and *Nosticzius* 1983).

The plant absorbs most of the sulphur through the root in the form of sulphate ions, a slow process. In addition, plants also absorb sulphur dioxide from the air through their leaves. High concentrations of sulphur dioxide near industrial areas can be harmful (toxic) (*Loch* and *Nosticzius* 1983).

Sulphur is found in both organic and inorganic forms in plants. There is no fixed ratio between the two fractions. The inorganic fraction, i.e. sulphate, is the sulphur reserve. As the sulphur supply increases, the inorganic sulphur content of the plant increases.

Sulphur is also very important as a building block. Disulphide bridges, for example, greatly stabilise the structure of proteins by linking polypeptide chains. Cysteine and methionine are the most abundant sulphur-containing proteins. In plants, high protein content is usually associated with high sulphur content. Its accumulated mass in tissues is 0.2–0.7% on a dry matter basis (*Loch* and *Nosticzius* 1983, *Terbe* 2018). It is found in highest concentration in leaves, followed by the yield. It is mostly stored in the form of sulphate (up to 60% of total sulphur) (*Terbe* 2018).

In Hungary, superphosphate and precipitation annually release several times the amount of sulphur extracted by crops. Whether the sulphur balance is positive or negative is also influenced by leaching.

The sulphur requirement of grain maize is 20–25 kg/ha. Inadequate sulphur supply leads to disturbances in protein synthesis. In the case of sulphur deficiency, the amount of soluble nitrogen compounds increases and protein content decreases. Inhibition of protein synthesis is indicated by the accumulation of amino acids that are normally absent or present in low amounts (e.g. arginine).

A sulphur-deficient plant is more underdeveloped, with the deficiency first appearing on young leaves. From older parts of the plant, it is not or very difficult to transform into shoots (*Terbe* 2018).

The symptoms of sulphur deficiency are similar to those of nitrogen deficiency. When sulphur supply is poor, the leaf plate turns yellow, first the tissue between the veins shows a lighter discolouration, then the thinner veins turn yellow, leaving only the main vein and its immediate surroundings green (*photo 1.6*). The difference in colour (between the main vein and the tissue) is not as pronounced as for potassium or magnesium. Over time, shoot growth slows down and stops. Sulphur-deficient plants are stiffly stiff. In severe cases, there is also a slight reddish discolouration on the backside.

In contrast to nitrogen deficiency, sulphur deficiency is observed on the youngest leaves (becoming spoon-shaped, leaf edges crinkling) (*Loch* and *Nosticzius* 1983, *Terbe* 2018).

Sulphur toxicity is rare, possibly if the soil contains too much sulphate, and sensitive plants may show yellowing spots from the leaf edges inwards and signs of scorching. Leaf size may be below normal and premature senescence may also occur.

2.9. Main microelements

Plants, as the first link in the food chain, are particularly important and form a significant part of the diet of humans and animals (*Winiarska-Mieczan et al.* 2019). The main source of micronutrients for plants is soil (*White* and *Brown* 2010). In many areas, soil is deficient in micronutrients – especially Zn and Fe – which not only reduces crop yields but also affects food quality (*Kanai et al.* 2009, *Manzeke et al.* 2014). This is a direct cause of ‚hidden hunger'. It is a global problem, affecting about one third of the world's population (*Harding et al.* 2018).

The most important micronutrient for maize production is *zinc*. However, zinc intake has received much less attention than nitrogen (N), phosphorus (P) or irrigation during the green revolution (*Tilman et al.* 2002, *Mueller et al.* 2012). Due to the high zinc requirement of maize, even in well-supplied maize growing regions under intensive cultivation, many agricultural areas show a zinc deficiency in the stands, to which the crop is sensitive (*Kalocsai et al.* Nearly 50% of domestic soils have a medium or lower zinc supply (*Kádár* 2005, *Kalocsai et al.* 2006, *Schmidt et al.* 2009), but in some areas, such as Fejér and Békés counties, the proportion of soils with poor zinc supply can reach 85–87% (*Matus* 2016). There are also large differences between soil types. Sandy soils have a low zinc content (30 mg kg/ha), forest soils have a medium zinc content (70–115 mg kg/ha), while chernozem soils have a zinc concentration of 120–150 mg kg/ha (*Győri* 1984). The upper ploughed layer of the soil (0–30 cm) contains the majority of the zinc available for plant uptake, with zinc contents ranging from 90–450 kg/ha. The amount of mobile zinc is only 1% of this value, so the amount of mobile zinc forms is only 1–5 kg/ha (*Szabó et al.* 1987, *Kádár* 2002).

As the pH of the soil increases, the binding of zinc to soil minerals increases, so its mobility is low, especially in neutral and alkaline soils. In acidic soils, the water-soluble and exchangeable zinc content is significantly higher than in neutral or alkaline soils (*Sims* 1986, *Wang et al.* 2012, *Smith* 1994, *Bákonyi* 2013, *Matus* 2016).

Zinc plays an essential role in the formation of stable metallo-enzyme complexes in plant cells (*Füleky* 1999) and is an important component and activator of several enzymes regulating metabolic processes (*Broadley et al.* 2007, *Hänsch* and *Mendel* 2009). In its absence, maize growth is stunted, generative organs are damaged, flower formation is delayed or even absent, which can reduce the yield per hectare by up to 80% (*Kalocsai et al.* 2004b).

Zinc deficiency causes young maize leaves to turn light yellow, almost white (bud whitening) (*photo 1.7*). On older leaves, whitish to pale yellowish chlorotic streaks appear on both sides of the midvein. These run from the leaf base to the tip, but the midvein, leaf edges and leaf tip remain green. The fine striping becomes wider as time goes on (*Photo 1.8*). In case of persistent absence, the leaf turns grey, bronze and then necrotic (*Buzás* 1983, *Patócs* 1989, *Kalocsai et al.* 2004b, *Kramer* and *Clemens* 2005).

The concentration of Zn in the plant is 25–150 mg/kg dm. In the early growth stage, the sufficient Zn concentration for the whole plant is 20–70 mg/kg (*Camberato* and *Maloney* 2012). Toxicity occurs above 400 mg/kg dm. General rates of zinc supplementation through soil application are 3–10 kg/ha of active ingredient, but 30–50 kg/ha of Zn is allowed in justified cases (*Kalocsai* 2006).

Soil application of Zn fertiliser successfully increases grain yield of maize (*Abunyewa* and *Mercie-Quarshie* 2004, *Potarzycki* 2010, *Matías* 2016, *Liu et al.* 2017, *Zhang et al.* 2020) by improving pollen viability, seed number and grain weight at the growing tip (pical) part of the grain, and also contributes to grain Zn biofortification (*Liu et al.* 2020).

Chlorophyll content of maize leaves increased by 8%, flow rate by 30% and root hydraulic conductivity by 177% with 20 kg/ha Zn treatment under irrigated conditions compared to control (no Zn) treatment, and by 18%, 46% and 52% with 50 kg/ha Zn under drought stress. There was also a significant increase in relative leaf water content under drought stress at 50 kg/ha and under irrigated conditions at 20 kg/ha Zn treatment. Under drought stress at 50 kg/ha and under irrigated conditions at 20 kg/ha Zn fertiliser treatment increased maize yield by 12.5% and 7.5%, respectively, and water use efficiency (WUE) by 11 and 6.5% compared to controls. These results demonstrated that in alkaline soil conditions under drought stress, 50 kg/ha Zn can effectively improve the water absorption capacity of maize, thereby increasing yield and WUE, while 20 kg/ha Zn is sufficient under irrigated conditions (*Zhang et al.* 2020).

The total *iron content* of the soils is between 0.5 and 5.0%, i.e. relatively high. The soluble iron content of soils is generally small, increasing with decreasing pH, and only in highly acidic soils such as podzols is it significant. Iron mobility is good in acid soils. As a consequence, the soluble iron content of topsoil is washed into the deeper layers where it precipitates. The chelates protect the iron from precipitation, the iron chelates remain in solution. Fe^{3+} ions are stable only below pH = 3, above which they precipitate, whereas Fe^{2+} ions precipitate only near the neutral point in the form of iron hydroxide. The uptake of iron is essentially determined by the chemistry and oxidation-reduction conditions. In acidic media, iron compounds are highly soluble, but solubility decreases with increasing pH. Iron deficiency can occur in alkaline soils (*Lead* 1999), most commonly in carbonate sands (*Loch* and *Nosticzius* 1983).

Iron is essential for respiration, chlorophyll formation, photosynthesis and protein formation (*Briat et al.* 2007, *García-Bañuelos et al.* 2014). Plants take up iron in the form of Fe^{2+}. An exception is grassland plants, which utilise iron as Fe^{3+}. The migration of iron in plants is limited. Only a small fraction of the iron content in plants is water soluble, about 80–90% is bound to organic compounds. 90% of the iron in plants is found in chloroplasts.

In iron deficiency, chlorophyll content decreases, protein synthesis is inhibited, and the amount of reducing sugars and organic acids increases.

In iron deficiency, not enough chlorophyll molecules are synthesised in chloroplasts, leaves do not turn green (*photo 1.9*), young leaves become lighter and yellowish, while the veins remain green. Monocots show characteristic longitudinal leaf striations. In cases of severe deficiency, the leaves are almost completely whitened and the veins of the leaves are not separated from the rest of the leaf plate. Reduced shoot growth, leaf and shoot dieback may occur, leading to significant yield loss (*Kanai et al.* 2009).

The concentration of iron in the plant is 20–200 mg/kg dm. In the presence of iron excess, leaves show an intense dark or blue-green discolouration, root and shoot growth is severely inhibited and roots turn brown. In very severe cases, the leaves wither. However, the development of iron excess is not typical.

Manganese occurs in soils, silicates, carbonates ($MnCO_3$) and oxides in the form of compounds with chemical equivalents II, III and IV. Mn^{2+} ions are mainly bound to the adsorption complex of the soil or are free in the soil solution. Plants can only take up the divalent ions. Manganese compounds in which manganese is present in a higher valent form are difficult to dissolve. Manganese ions and compounds of different valency can be converted to each other by oxidation and reduction, the conversion depending on the redox potential of the soil. In poorly aerated soils at low pH, significant amounts of manganese can be reduced. Increased concentrations of Mn^{2+} ions can sometimes have toxic effects. In neutral or weakly alkaline soils, the balance may shift towards manganese compounds of III and IV values to such an extent that the manganese supply to plants is not assured (*Loch* and *Nosticzius* 1983). In alkaline soils, the uptake of manganese by plants is inhibited. Long, prolonged drought, soil compaction, inland water, and post liming also result in manganese deficiency in most cases.

Manganese has a function in plant metabolism as an enzyme activator similar to magnesium and iron. It acts in the citric acid cycle, in the formation of lipids and in photosynthesis. Acts in the formation of carbohydrates. It also increases the vitamin C content of vegetables (*Loch* and *Nosticzius* 1983). Manganese is involved in chlorophyll formation and photosynthesis, has a positive effect on yields and promotes the formation of lateral roots, thus enabling the plant to take up more nutrients from the soil. It accelerates germination and development in the early stages and increases the availability of P and Ca.

In case of manganese deficiency, alternaria leaf spots occur in monocots. This starts in spring on young leaves in the form of dirty grey streaks or spots. The leaves later break. Alternaria leaf spots can also occur in other cereals, but to a lesser extent. In dicots, net or mosaic chlorosis occurs between the leaves of the highest mature leaves, later the leaf tissues die and brown spots or blotches appear *(Photo 1.10*).

The concentration of manganese in plants is 20–200 mg/kg dm and its mobility in plants is limited. Toxic effects occur when soil manganese content is high, especially in acid soils. Furthermore, since manganese is also a constituent of some fungicides, it may accumulate with repeated application of fungicides, especially in plants grown on sandy soils. Manganese poisoning can occur during wet periods, as stagnant water can also induce or enhance manganese toxicity, as anaerobic conditions reduce higher oxides of manganese to the Mn^{2+} available to plants. As the soil dries out, plants recover.

Among the micronutrients, *boron* is the only non-metallic element, an essential micronutrient. Boron is found in soil, mica and minerals. Silicates (glauconite, muscovite) contain calcium borates. Part of the boron is found in the form of boric acid (H_3BO_3) or borates as a result of the decomposition of organic compounds or weathering processes. It can occur in soil solution as free anions and bound to soil particles. It is present in soils at 2–200 mg/kg, with an average of about 30 mg/kg in dry matter. Boron is taken up by plants as borate ions (*Loch* and *Nosticzius* 1983).

Boron is a component of the cell wall structure. More than 90% of the boron in a cell is found in the cell wall. It plays an important role in cell development and division, tissue differentiation, cell membrane permeability and cell wall formation (*Bolanos et al.* 2004, *Godlbach* and *Wimmer* 2007, *Camaco-Cristóbal et al.* 2008). Boron is also very important for the development and function of reproductive plant organs. Their development requires higher boron levels than the growth of vegetative organs. Boron has a very positive effect on pollen formation and maturation, pollen ear growth and structure, and fertilisation (*Wimmer et al.* 2015).

In boron deficiency, the chlorophyll concentration of the plant decreases (*Kastori et al.* 1995), the photosynthesis intensity decreases (*Plesničar et al.* 1997), and the carbohydrate transport is disturbed (*Kastori et al.* 1995), which affects the uptake of ions and thus the water balance. The accumulation of carbohydrates also results in slower protein synthesis (*Kastori et al.* 1995), an increase in soluble nitrogen compounds (*Kastori* and *Petrović* 1988), and a decrease in yield and quality (*Kastori* 2017).

Boron does not move easily in the plant, so the deficiency is most noticeable in younger tissues. In the absence of boron, chlorosis or necrosis develops on the youngest leaves, shorter internodal spaces are formed; the shoot and shoot tip die; the leaf and petioles thicken and become brittle; the petioles and stems become wilted; increased shoot formation from lateral buds; less flower and seed formation; inhibited root growth – at the same time abnormally many adventitious roots are formed, which are brownish, slimy. The classic signs of boron deficiency in maize are small white spots and waving of leaves. They appear as scattered white spots between the veins (*Photo 1.11*).

The concentration of boron in dry matter is <10 mg/kg dm in monocots and 20–100 mg/kg in dicots (*Loch* and *Nosticzius* 1983). Maize is a boron-rich plant. Toxic effects occur at concentrations greater than 100–200 mg/kg in dry matter. Signs of boron excess are manifested as necrosis, first appearing on the margins and tips of older leaves, then extending to the whole leaf and gradually to the other leaves. Finally, the whole plant dies (*Kastori* 2017).

Molybdenum is found in soil mainly in the form of molybdenate (MoO_4^{2-}), and its behaviour is therefore very different from that of other heavy metals (Fe, Mn, Cu, Zn). For this reason, the supply of molybdenum to plants in acid soils is compromised, but can be improved by liming. It is present in the smallest amounts in sandy soils (0.34–0.50 mg/kg), mineral soils have a molybdenum content of less than 1 mg/kg. It ranges widely in forest soils (0.25–1.0 mg/kg) and chernozem soils (0.31–1.48 mg/kg) and is most abundant in poorly aerated hydromorphic (meadow and marsh) soils, where it can reach up to 4 mg/kg. Continuous sulphate addition interferes with molybdenum uptake (*Loch* and *Nosticzius* 1983, *Győri* 1984).

Molybdenum is an important metal component of enzymes involved in nitrogen metabolism. It plays a key role in atmospheric nitrogen fixation, nitrate reduction (*Srivastava* 1997), xanthine dehydrogenase, aldehyde oxidase and sulphite oxidase (*Zimmer* and *Mendel* 1998, *Schwarz et al.* 2009, *Mendel* and *Kruse* 2012).

When molybdenum is deficient, the leaves turn greyish green and the middle and older leaves become chlorotic (*Photo 1.12*), then curl, the petiole elongates, growth is stunted, and when flowering is abundant, formation is extremely poor and extensive. Often causes symptoms similar to nitrogen deficiency. It appears in patches in the field. Deficiency symptoms occur at concentrations below 0.1 mg/kg.

Molybdenum is the smallest of the nutrients taken up by the plant, with dry matter molybdenum content usually less than 1 mg/kg. The maize plant contains 0.400 mg/

kg molybdenum, but the molybdenum content of plant parts varies greatly, with 0.250 mg/kg in the grain and much less in the stalk (*Szabó et al.* 1987). Much molybdenum is present in alkaline soils with high lime content and in floodplain areas, where it can accumulate in high concentrations. Plants can take up significantly higher amounts of molybdenum without any adverse effects on their development, in this respect differing from the effects of other heavy metals (*Anke* and *Seifert* 2007). Toxic effects are not typical, depending on the concentration of some amino acids (methionine, cysteine). It occurs in leaves at levels above 100 mg/kg and inhibits shoot and root development. Symptom is reddish-yellow to orange-yellow chlorosis of leaves (*Kevresan et al.* 2001).

Most of the *copper* is bound to organic or inorganic adsorption surfaces in the soil in divalent form. Copper mobility in soil is very low, but increases with decreasing pH (soil acidification). The copper content in the soil section mostly decreases from the surface downwards.

Plants absorb Cu^{2+} from the soil as Cu ions, but can also absorb smaller amounts in the form of various organic complexes.

It is a constituent of enzymes involved in respiratory metabolism and electron transport. It plays a role in photosynthesis and in carbohydrate and protein synthesis (*Demirevska-Kepova et al.* 2004, *Guo et al.* 2010). Copper is also important for disease resistance in plants (*Tomazela et al.* 2006). Copper-deficient plants accumulate organic acids such as aspartic acid. Copper protects the chlorophyll from premature degradation, and thus the assimilation activity of the plant is more intense. Copper participates with iron in nitrate reduction.

Copper deficiency adversely affects the formation of generative organs, leading to yield loss. Copper can also displace other metal cations from the chelates and the root surface of the plant. It is strongly bound to the root; the copper content of roots is usually significantly higher than that of other plant organs.

In the case of copper deficiency, a yellow interveinal discoloration of the young leaf is visible, the leaf base is uniform yellowish green (*Photo 1.13*), and narrow, aggregated leaves are formed (*Bouazizi et al.* 2010). Poorly supplied plants show reduced grain formation and reduced yields (*Luchese et al.* 2004). Deficiency symptoms are mainly observed in soils with high organic matter content, in sandy podzolic soils with copper deficiency and in carbonate soils. It can be managed by both soil and foliar fertilisation.

The concentration of copper in the plant is 5–10 mg/kg dm. Copper excess or toxicity may occur in highly acid soils where soluble copper content increases. The symptoms of copper excess are similar to those of Fe deficiency. Root growth is poor, colour darkens and root tips die. Younger leaves turn a strong dark green colour.

2.10. Main interactions between macro- and microelements

Of the three most important nutrients, nitrogen is the primary determinant of maize yield in most soils under Hungarian conditions (*Bocz* 1976), increasing its nitrogen content and also positively influencing the plant's uptake of phosphorus (*Szalka* 1996). This interaction is also true in reverse, with increasing phosphorus rates having a positive effect on nitrogen fertiliser efficiency (*Bennett et al.* 1654, *Szirtes* 1971).

NxP interactions can modify the Fe, Mn, Cu content of maize more strongly than direct Fe, Mn or Cu fertilisation. The stalk responded to the soil supply with a luxurious uptake, and at the same straw weight, showed a sevenfold increase in Cu and a threefold increase in Mn. Zn supply dropped to one third in plots well supplied with P (*Csathó et al.* 2017).

According to *Kádár* (1993), the plant takes up potassium without damage and releases it when unnecessary. However, overfertilisation of potassium is unfavourable, as it induces antagonism for several microelements. Crop weight is controlled by PxK supply, e.g. N effects are neglected in dry years. Excessive P has been shown to reduce grain number, grain weight per thousand and grain yield at harvest. A one-sided P predominance resulted in a grain yield of 3.4 t/ha, whereas a balanced P supply resulted in a grain yield of 6.2 t/ha (*Kádár* 2000).

In maize production, zinc is of particular importance for improving pollen viability (*Sharma et al.* 1990) (*Loch* and *Nosticzius* 1983). In the case of phosphorus excess, we have to expect a relative Zn deficiency in our stands due to PxZn antagonism, which may result in significant yield loss and quality deterioration (*Csathó* and *Kádár* 1989, *Csathó* 1992, *Kalocsai et al.* 2004a, *Zhang et al.* 2017, *Bindraban et al.* 2020). Low-dosage phosphorus fertiliser limits zinc deficiency by migration into shoots, while high-dosage phosphorus fertiliser slows down root surface absorption (*Safaya* 1976, *Simkó* and *Veres* 2019). Analytical data from samples taken at the five-leaf and ten-leaf stage showed that increasing fertiliser rates decreased Zn content, while P content increased significantly. Data from the leaf analysis at harvest showed no change in P content, a slight decrease in Zn content and a decrease in Zn content of the husk leaves under both irrigated and non-irrigated conditions. The amount of tryptophan as a proportion of total protein also decreased with the decrease in zinc content. Phosphorus-zinc antagonism has also been demonstrated in modern hybrids (*Győri* and *Sipos* 2005).

As potassium uptake in maize increases, calcium and magnesium uptake may decrease (*Andrejenko* and *Kuperman* 1961). High-dose K treatments have altered the ion ratios in the soil, resulting in a decrease in the Ca and Mg content of the plant (*Kincses et al.* 2002).

Of the microelements, the Cu content is not affected by NPK fertilisation. Manganese content increases due to the solubilising effect of acid superphosphate, and zinc content decreases significantly, especially when high doses of phosphorus fertilisers are applied (*Andrejenko* and *Kupermann* 1961, *Olson et al.* 1965, *Tisdale* and *Nelson* 1966, *Prohászka* and *Cserni* 1969, *Prohászka* and *Gurabi* 1972, *Patel* and *Mehta* 1973, *Takkar et al.* 1976).

The calcium-strontium correlation has been demonstrated by *Győri* and *Sipos* (2005), i.e. increasing fertiliser rates increase strontium content in addition to calcium.

The manganese and zinc content of maize decreases significantly with increasing soil moisture, but its uptake increases with yield growth (*Nambiar* and *Cottenie* 1971).

The application of Zn-Fe soil spray had a significant effect on maize yield (+30%) and net photosynthetic rate (+92%). The crude protein content of maize increased significantly from 8.39% to 9.91% and crude fibre from 10.81% to 15.96%. The results demonstrate that the use of Zn-Fe combination can be an alternative method to improve maize growth and quality in Zn and Fe deficient regions (*Mugenzi et al.* 2018).

3. Interaction between fertilisation and other crop production factors

Recent research also shows that there are significant differences in fertiliser response between *maize hybrids.* In order to determine these differences, it is worth investigating the fertility and fertiliser response of the hybrids in a multi-stage dose experiment (*Nagy* 2005).

In line with *Győrffy* (1976), the experimental results of *Nagy* (2005) also indicate that the natural nutrient utilisation capacity should be taken into account in addition to the fertiliser response. For some of the hybrids studied, the relationship between nutrient supply and yield can be described by a new type of yield curve. The new relationship differs from the previously known extensive and intensive types in that the yield curve starts from a high level and increases with fertilisation (*Figure 9*). Such hybrids not only have an excellent nutrient response but also an excellent natural nutrient utilisation capacity.

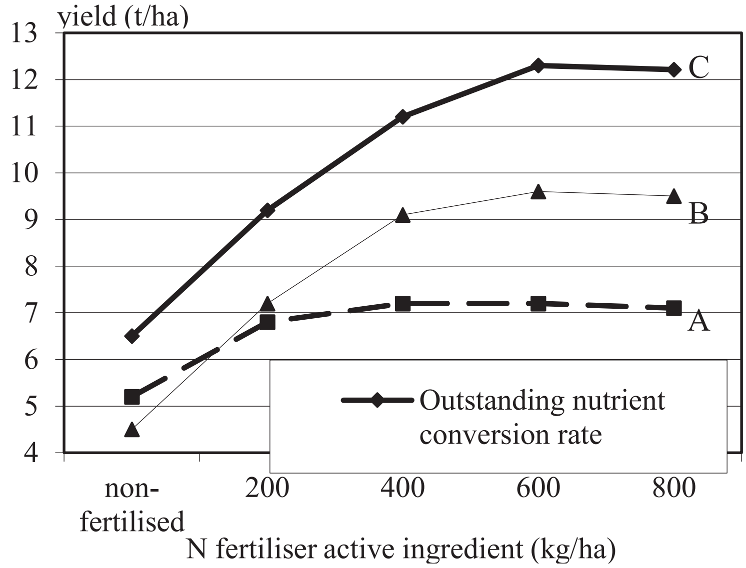


Figure 9. Fertiliser response of different maize hybrids (Type A and B *Győrffy* 1979, Type C *Nagy* 1987)

Water availability plays a major role in the conversion of the active substances of fertilisers, especially nitrogen (*Bocz* 1976), and the water availability of the plant depends on the amount of precipitation, the agrotechnology, tillage, fertilisation, irrigation and crop density (*Figure 10*) (*Nagy* 2005).

The phyto mass production of maize was increased by 13.6–27.5% by fertilisation (*Nagy* 1978). The average total plant mass was highest in the 120 kg N/ha treatment. Further increase in fertiliser rate did not result in any increase. In irrigated stands, higher fertiliser rates also had a positive effect (*Figures 11–12*).

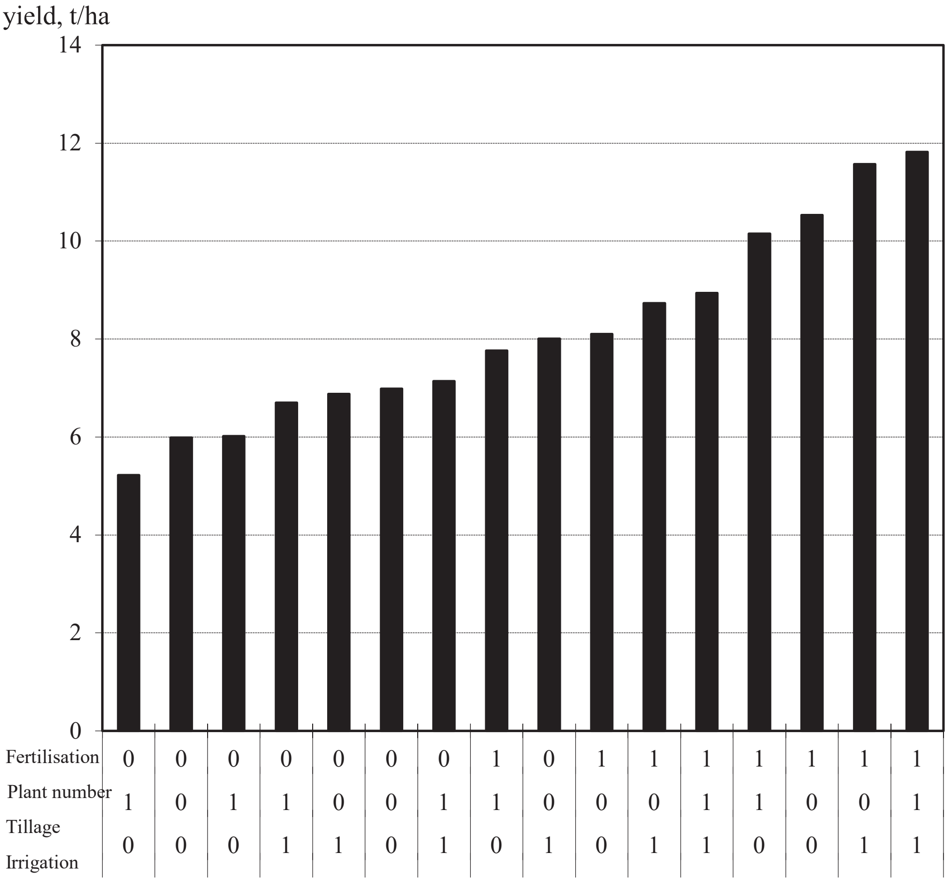


Figure 10. Effect of a combination of crop production factors on maize yield
(Source: *Nagy* 2005)

Fertilisation	0 = no fertilisation, 1 = 120kg N, 90kg P O$_{25}$, 106kg K O/ha$_2$
Plant number	0 = 60.000/ha, 1 = 80.000/ha
Cultivation	0 = no ploughing, 1 = autumn ploughing
Irrigation	0 = not irrigated, 1 = irrigated

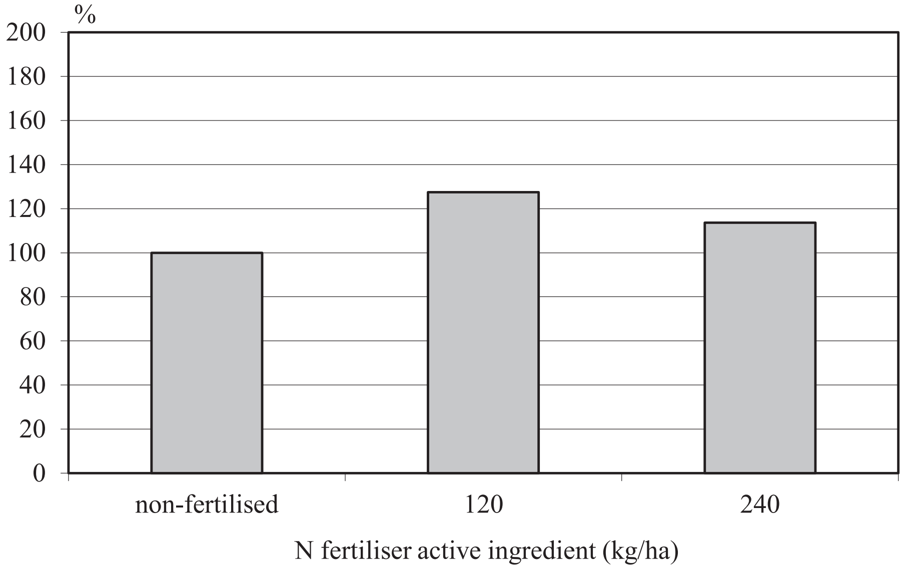


Figure 11. Effect of fertiliser application on the above-ground phyto mass of maize
(Source: *Nagy* 1978)

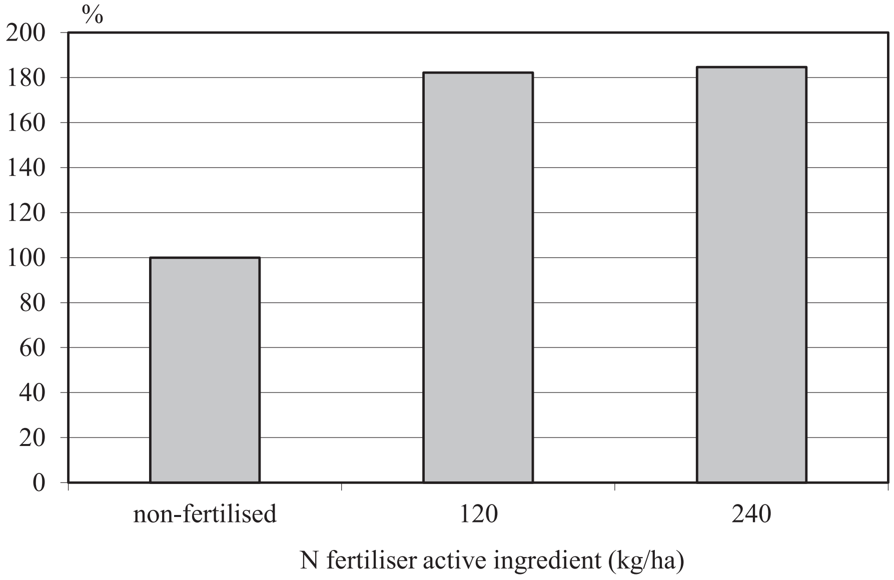


Figure 12. Effect of fertiliser application
on above-ground phyto mass of maize in irrigated stands
(Source: *Nagy* 1978)

Plant height of maize was positively affected by fertilisation, and the differences followed the magnitude of fertiliser application (*Nagy* 1978). The effect of fertilisation was significant in all cases compared to the control (*Figure 13*). The highest plant height was provided by nutrient levels of N180+PK *(Vári* 2012) and N120 and 150+PK (*Karancsi* 2015).

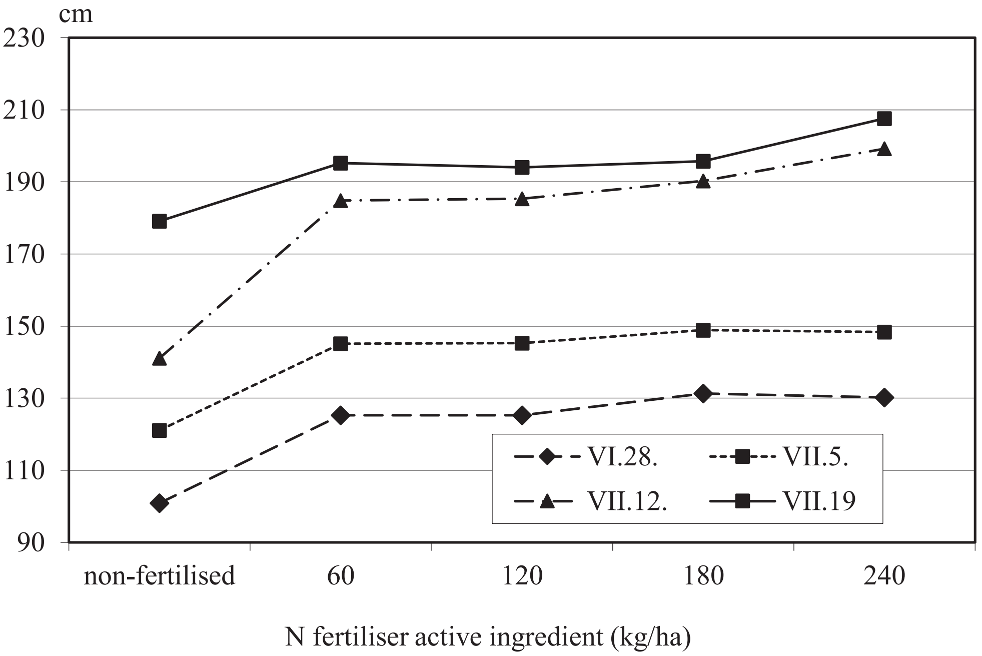


Figure 13. Effect of fertiliser application on maize plant height
(Source: *Nagy* 1997)

The stem diameter of maize in silty soils was determined by higher nitrogen levels of 200, 240 and 280 kg/ha (*Ullah et al.* 2015) (*Figure 14*). *Poorebrahimi et al.* (2018) showed an increase in stem diameter by increasing nitrogen from 80 to 240 kg/N ha.

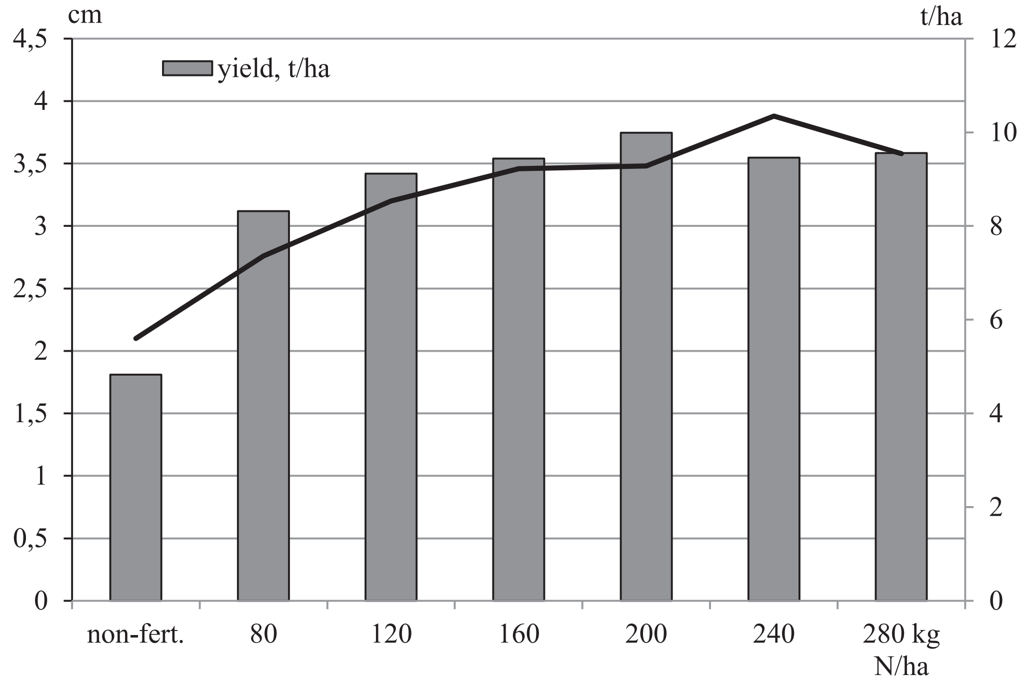


Figure 14. Effect of nitrogen fertilisation on stalk diameter and yield of maize (Source: *Ullah et al.* 2015)

The effect of nitrogen fertilisation on maize leaf area growth has been confirmed (*Tóth et al.* 2002, *Ma et al.* 2005, *Micskei et al.* 2009). Minimum LAI values were obtained with no fertilisation, maximum LAI values with 120 kg N+PK (*Molnár* and *Sárvári* 2007, *Jakab* 2003) and 280 kg/ha+PK (*Ullah et al.* 2015). As phenological stages progressed and nutrient doses increased, LAI increased and then decreased during the grain filling period (*Karancsi* 2015). Adequate N supply can promote the initial rapid growth of maize leaf area, thus maintaining optimal LAI for a longer period, biomass persistence, which is beneficial for the flow of assimilates to the grain yield, and harvest index (*Anderson et al.* 1985, *Berzsenyi* 1988, 1993ab, *Cheema et al.* 2010). However, this advantage is not economically beneficial in drought because maize is subject to earlier water deficit, which peaks in the reproductive stage and consequently may result in yield losses (*Ruzsányi* 1981).

Berzsenyi (1996) studied the effect of N fertilisation (0, 80, 160, 240 kg N/ha) on the growth and growth dynamics of maize (*Zea mays* L.) using the computer growth analysis program of *Hunt* and *Parsons* (1974) with two different genotypic hybrids in 5 consecutive growing seasons. Plant samples were taken 13–16 times for the destructive growth analysis. By comparing the results obtained with the Hunt-Parsons program and the logistic function fitting, it was found that the growth dynamics of dry matter production and the absolute growth rate were well characterised by both approaches. However, the Hunt-Parsons program had a clear advantage in terms of relative growth rate (RGR), net assimilation rate (NAR), and was therefore the only model suitable for characterising the seasonal dynamics of leaf area.

According to the yield element study, the relationship between *number of ears per ha* and yield t/ha is consistent (*Nagy* 1978). Increasing nitrogen doses increased the amount of yield-forming elements in maize and thus its yield (*Torbert et al.* 2001, *Hejazi* and *Soleymani* 2014).

Fertilisation increases the *ear length*, which varies depending on the hybrid and the year. *Karancsi* (2015) obtained the highest value with N90-150+PK, *Ngosong et al.* (2019) 150 and 200 kg/ha treatments. *Poorebrahimi et al.* (2018) showed an increase in ear length by increasing the nitrogen application rate from 80 to 240 kg/N ha-1. Studies of maize ear yield indices under non-irrigated conditions showed that maize ears were 20–23% longer in fertiliser treatments compared to the non-irrigated control (*Figure 15*). The *number of grain rows* on maize cobs showed the least change with fertiliser application and irrigation.

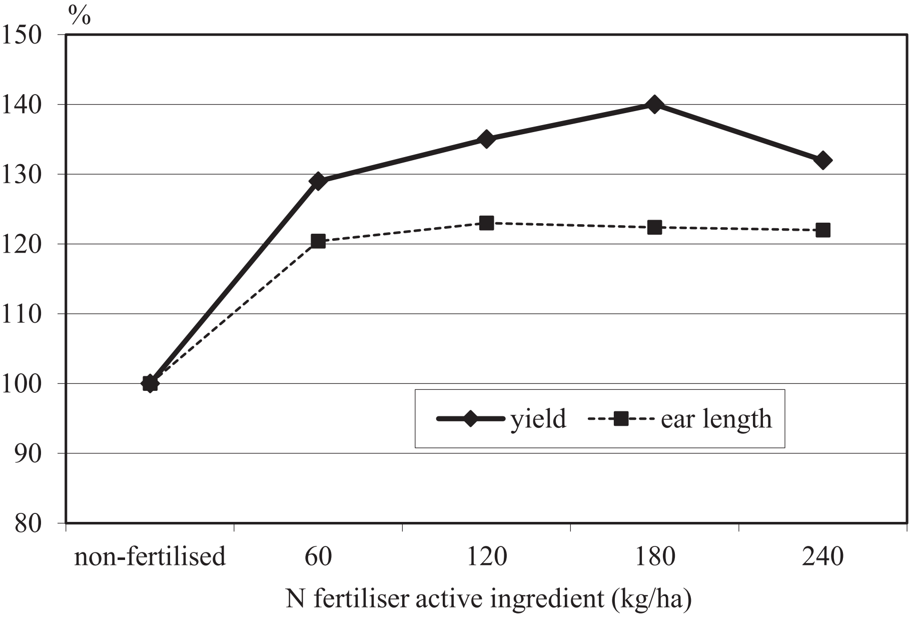


Figure 15. Relationship between maize yield and ear length
(Source: *Nagy* 1978)

Optimal nutrient supply contributes significantly to the increase in the *number of grains per ear,* the *thousand-grain mass* (*Bocz* and *Nagy* 1981). In the Debrecen experiments, fertilisation increased the number of *grains per ear* more than irrigation, and the number of grains per ear increased significantly on all nutrient levels. Fertilisation increased yields by 25–32% and positively influenced the thousand grain weight of maize (*Figure 16*).

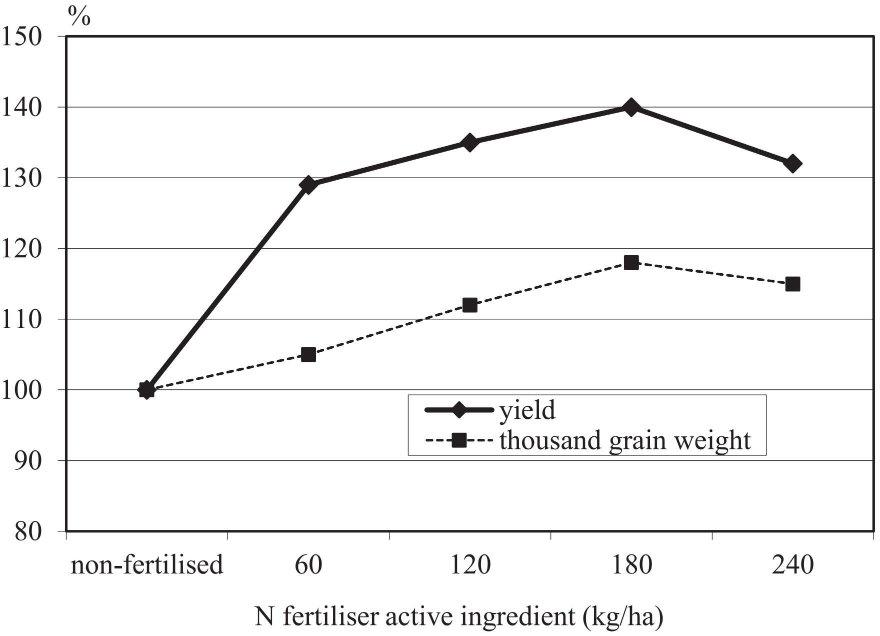


Figure 16. Relationship between maize yield and thousand grain weight
(Source: *Nagy* 1978)

In an experiment at Martonvásár, fertilisation reduced the thousand kernel weight of maize grains on average over several years in a large growing area, because fertilisation significantly increased the proportion of second ear (*Győrffy et al.* 1965). In medium or more than medium-dense stands, the effect of fertilisation on thousand kernel weight was reliable. Over an average of 5 years, fertilisation increased the thousand-grain weight of maize by 24 and 35 grams for 0.24 m^2 of growing area, respectively.

Fertilisation has a significant effect on the ratio of *grain to other plant parts* (*Nagy* 1978). Without fertilisation the ratio is 1:1.22, with N_{180} and N_{240} treatments 1:0.99 and 1:1.03 (*Figure 17*). In irrigated stands, fertilisation also had a positive effect on the grain-stem ratio. In the irrigated treatment, the ratio is wider. Irrigation resulted in a dry matter surplus of 1.065 t/ha of maize grain to a dry matter production of 2.3 t/ha of other parts of the crop. The average of the fertiliser treatments without irrigation was 1:1.04 and 1:1.18 in irrigated stands. Fertiliser application increased grain, leaf, cob and stem weight (*Figure 18*). The proportion of cob leaves decreased in the non-irrigated treatment and did not change significantly in the irrigated stand after fertiliser application.

The N, P, K, Ca and Fe content of the root mass was increased by fertilisation in both the non-irrigated and irrigated treatments. In irrigated treatment, it decreased Zn, Cu, Mn and did not affect Mg content. Irrigation increased root mass K, Mg, Fe and decreased N, Ca, Zn, Cu and Mn (*Nagy* 1978).

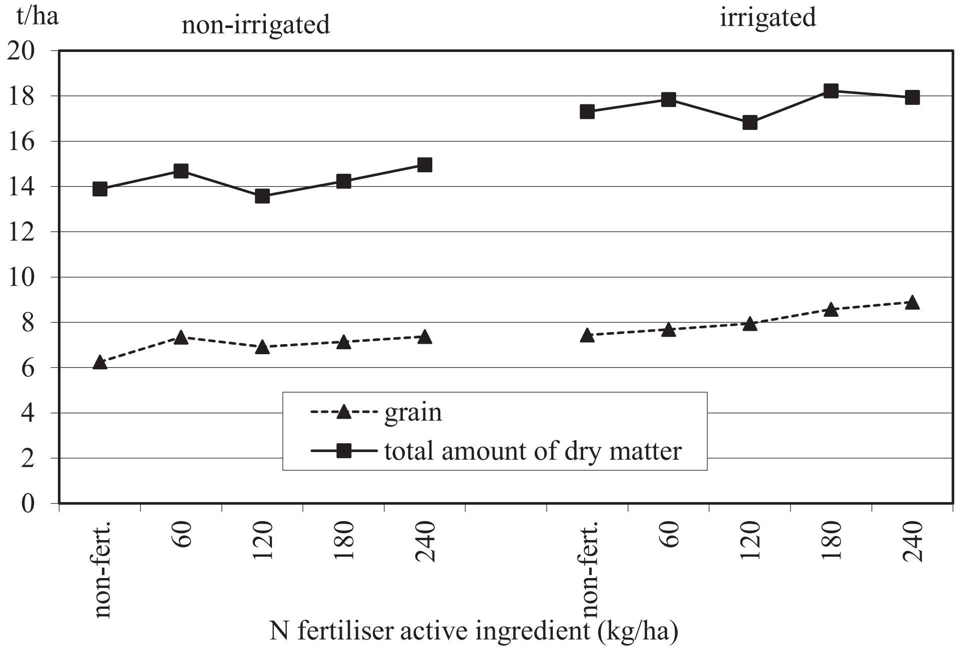


Figure 17. Effect of fertilisation
and irrigation on the proportion of grain and other plant parts
(Source: *Nagy* 2005)

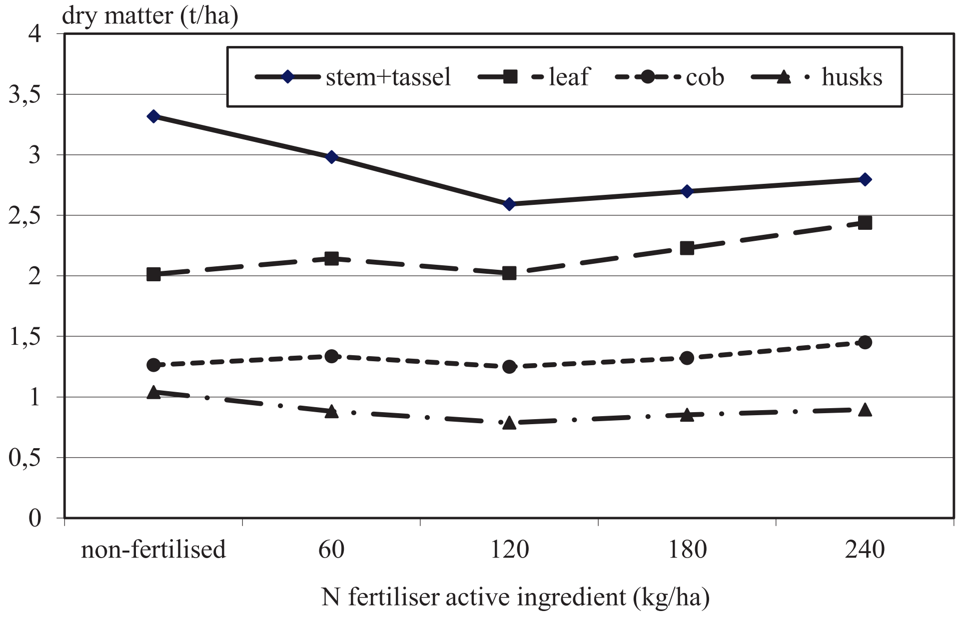


Figure 18. Effect of fertiliser application on the
dry matter distribution of plant parts in non-irrigated cropping
(Source: *Nagy* 2005)

In the literature, there are often references to the fact that fertilisation, especially nitrogen, can delay maize maturation. *Győrffy et al.* (1965) showed in their studies that the effect of fertilisation in delaying maturation is only apparent, due to the fact that maize leaves remain green longer when nitrogen fertilisation is applied, while there is no difference in the moisture content of maize ears and the crumbling rate.

4. Fertilisation and the crop year

Both domestic and foreign literature agree that the main factors influencing fertiliser use are weather, soil properties, forage, water supply, tillage, crop balance, and the nutrient response of the crop or variety/hybrid. The weather, as it regulates the heat and moisture supply of the growing area, influences the transformation of the soil, plant growth, nutrient uptake and thus the fertiliser prevalence (*Fehér* 1954, *Fekete et al.* 1967, *Bocz* 1976, *Láng et al.* 1983, *Biczók et al.* 1988, *Filep* 1988, *Nagy* 1995, 1988, *Szász* 1988, *Raven* 1993, *Ruzsányi* and *Pető* 1993, *Hall et al.* 1994, *Nagy* 1996, *Jolánkai* 2014). In the case of extensive technology, the crop yield is a determining factor in 40% of the year, and by applying intensive technology, the ecological negative effects can be significantly reduced (*Pepó et al.* 2019).

During drought, the plant develops well in the first half of the development, but in the second half, due to the high LAI and the increased water demand, maize is severely water stressed and as a consequence yield losses are significant (*Mándy* 1962, *Győrffy et al.* 1965, *Debreczeniné* 1969, *Debreczeni* and *Debreczeniné* 1983, *Nagy* 1997).

In the experimental plantation of the Research Institute of Cereal Production in Újszeged, Hungary, the effect of N fertilisation was examined year by year in an experiment on meadow alluvial soil. It is remarkable that in the year with favourable rainfall supply, the yield increase was not significant above 100 kg N/ha, whereas in the two dry years, the yield was significantly increased by 200 kg N (*Prokszáné et al.* 1995).

The results of the experiments at the Látókép Experimental Station of the University of Debrecen have shown that the differences between the yields of maize hybrids are greater the more stressful the conditions the plants have to endure (*Nagy* 1995). In dry years, only lower fertiliser rates (60 kg N/ha) are recommended, higher rates are not necessary. In wet years, higher doses (120 kg N/ha) resulted in significantly higher yields and higher nutrient use (*Nagy* 2012).

Decades of research by *Nagy* (2017) show that the fertiliser response of maize hybrids is significantly influenced by the season, especially by rainfall, which can be well characterised by the grain yield per 1 mm of rainfall (*Figure 19*). The results of *Széles et al.* (2018a) also demonstrated that fertiliser application significantly improved the water use efficiency of maize. In a wet year, water use efficiency increased from 19 kg mm^{-1} in the non-fertilised treatment to 29 kg mm^{-1} in the optimal 120:92:108 kg NPK/ha treatment. In a dry year, the yield per 1 mm of precipitation was 15 kg mm^{-1} in the non-fertilised treatment and increased significantly (32 kg mm^{-1}) in the optimal 180:184:216 kg NPK/ha treatment. *Pepó et al.* (2016) showed that optimal nutrient supply not only increases the yield of hybrids efficiently, but also the water use of genotypes. Compared to the relatively older (R_FAO 360) genotypes, the newer (Ú_FAO 380, Ú_FAO 390, Ú_FAO 470) maize genotypes showed a more favourable value (*Figure 20*). The water use efficiency of the longer duration hybrids (FAO 420 and FAO 490) was higher than that of the shorter FAO 320 hybrids (*Széles et al.* 2018a).

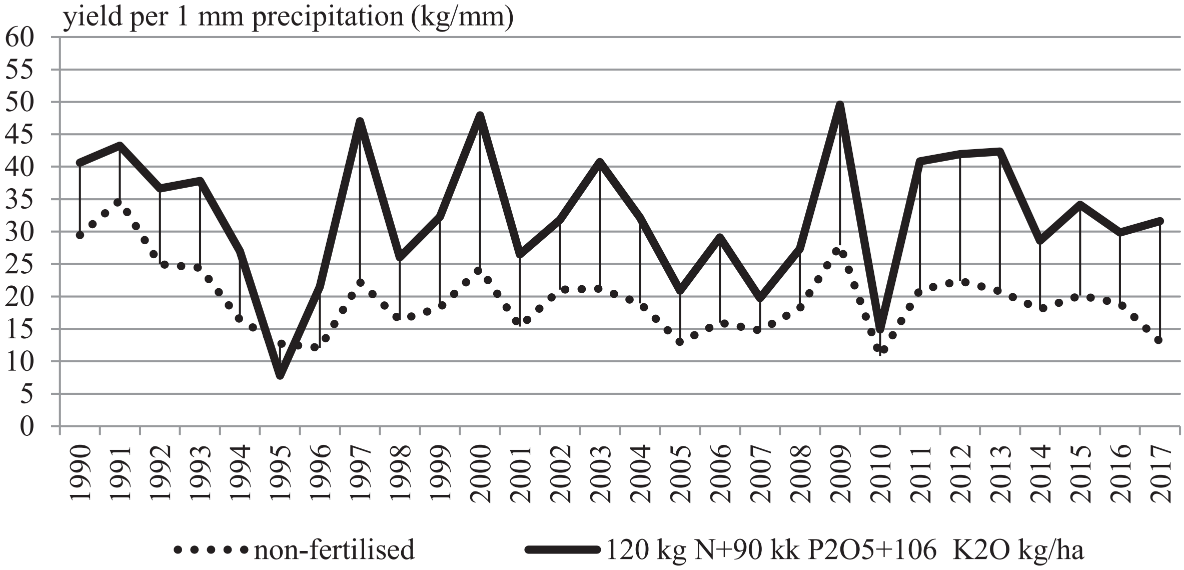


Figure 19. Maize grain yield per 1 mm precipitation, Debrecen, 1990–2017
(Source: *Nagy* 2019)

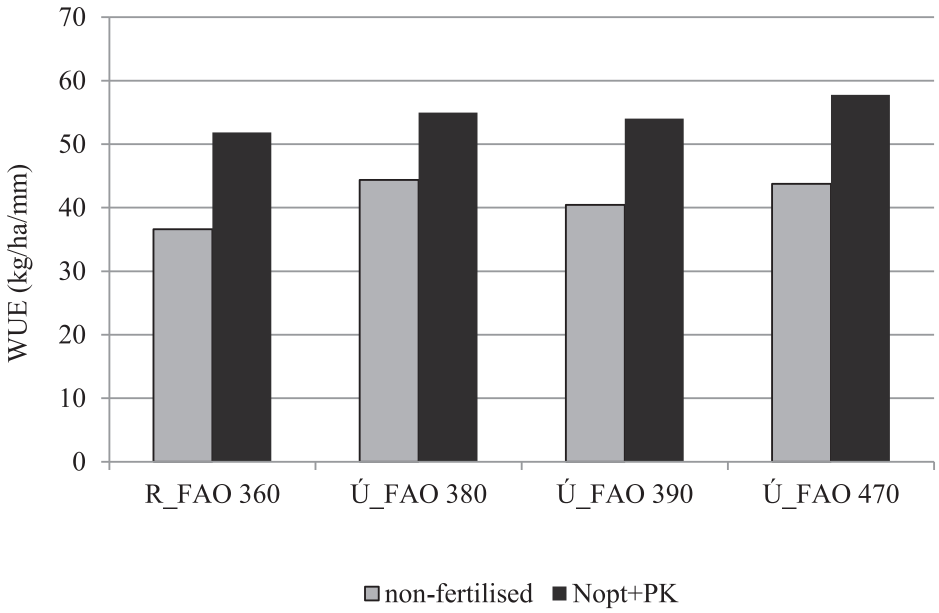


Figure 20. Effect of nutrient supply on specific water use of maize genotypes, Debrecen, 2012–2014
(Source: *Pepó et al.* 2016)

The yield enhancing effect of fertilisation can be quantified on a yearly basis and in each crop year, which is the basis for successful planning and management (*Figure 21*). There was a reliable difference between the maize yield of the unfertilised treatments and the 120 kg N/ha fertilised treatments in all years (regardless of whether it was a wet or dry year), averaging 4.947 t/ha over 20 years (*Nagy* 2017).

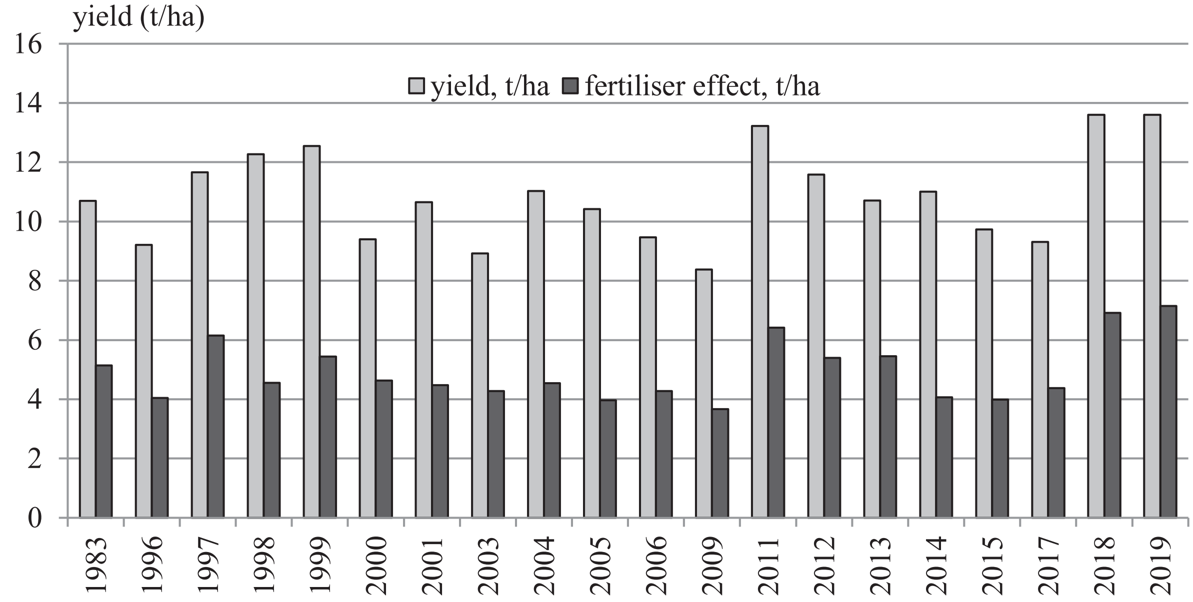


Figure 21. Effect of fertilisation and crop year on maize yield, Debrecen, 1983–2019
(Source: based on data from *Nagy,* own ed. 2019)

Márton (2015) investigated the effect of natural precipitation variability and the nutrients N, P and K on maize yield in 21 experimental years of the OMTK A-17 trial (Nagyhörcsök, Experimental Station of the Institute of Soil Science and Agrochemistry, MTA ATK). Out of the 21 maize experimental years, 9.5% had normal weather, 9.5% had dry weather, 42.9% had drought, and 38.1% had rainfall. Water deficit years (dry + drought) accounted for 52.4%. Compared to control soils in normal years, yields were characterised by significant equalised fertiliser inputs. One-sided N, deficient NP and NK fertilisation resulted in yield increases of 2.7 t/ha, 2.8 t/ha and 3.4 t/ha, respectively. Yield could be barely increased with the total NPK (8.3 t/ha) treatment. In drought, N, NP and NK fertilisation resulted in additional yields of 1.1 t/ha, 2.8 t/ha and 3.1 t/ha, respectively, which were not significantly increased by total NPK (3.2 t/ha) treatments. Treatments in the dry year experiments averaged 6.0 t/ha, 18% less than normal years. In drought, similar effects were recorded for N, NP, NK and NPK treatments. The average of treatments was 6.4 t/ha, 12% less than in normal years. In wet conditions, the positive effect of improved water availability was observed for the unilateral N and incomplete NP and NK fertilisation treatments (N: 43%, NP: 49%, NK: 59%). NPK treatments did not increase yields further. The average of treatments in the wet year experiments was 7.5 t/ha, 3% more than in normal years (*Figure 22*).

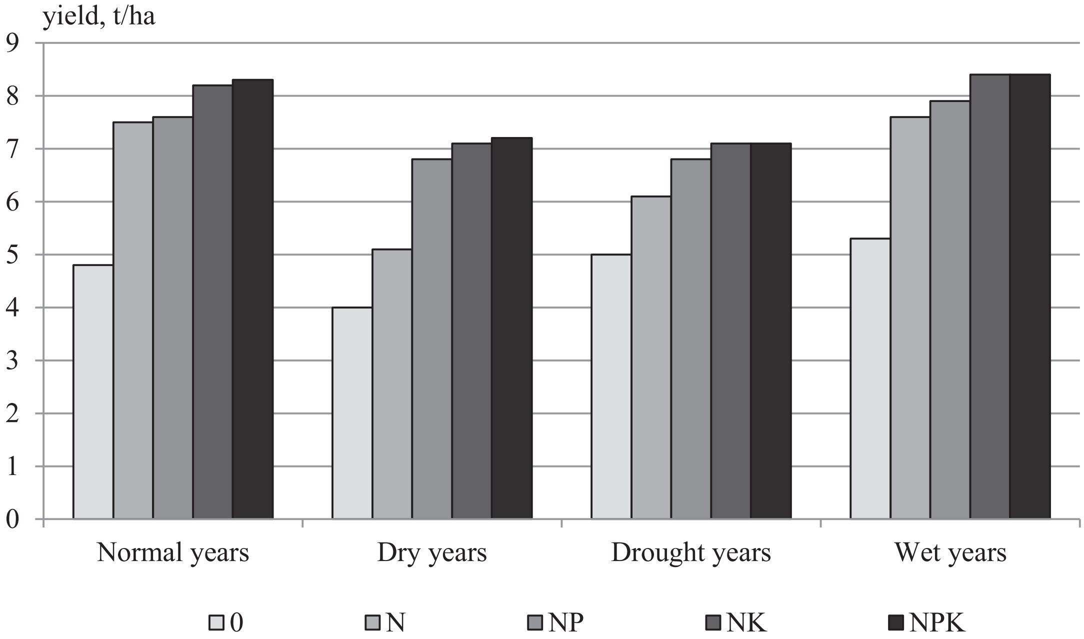


Figure 22. Effects of NPK fertilisation on maize yield in normal, dry, drought and wet years, Nagyhörcsög, 1969–2013
(Source: *Márton* 2015)

In the Debrecen long-term experiment, the results of the years (2011–2016) classified according to precipitation, effective heat sum (HU) and potential evapotranspiration (PET) confirmed the significant yield-limiting effect of precipitation deficit (*Figure 23*). Drought reduced maize yield by 16% ($P<0.001$) compared to the average year. The wet year resulted in a 19% yield increase ($P<0.001$). The variability of the weather is shown by the significant difference of 31% between dry and wet years ($P<0.001$). When evaluating the effect of NPK treatments, it was confirmed that under more favourable rainfall conditions, the 120:92:108 kg NPK treatment resulted in the highest yield, which was 26% higher than in the dry year (*Széles et al.* 2018b).

In addition to the amount of fertiliser, the correct NPK nutrient ratio should also be taken into account. For the increasing N+constant PK treatment combination group, the effect of the weather on yield was more significant (4,220 t/ha) than for the increasing N+equal PK treatment combination group (2,165 t/ha) (*Széles et al.* 2018a) (*Figure 24*).

The influence of soil properties depends mainly on the fertility of the soil, the thickness of the topsoil and the water balance (*Sarkadi* 1975, *Bocz* 1976, *Dezső* 1976, *Győrffy* 1976, *Láng* 1976, *Buzás* 1987, *Ruzsányi* 1992). Forage is a factor that can directly reduce or enrich soil water and nutrient reserves and, through other effects (weed cover), modify the fertiliser use (*Könnecke* 1969, *Kemenesy* 1972, *Kováts* 1974, *Győrffy* and *Berzsenyi* 1992).

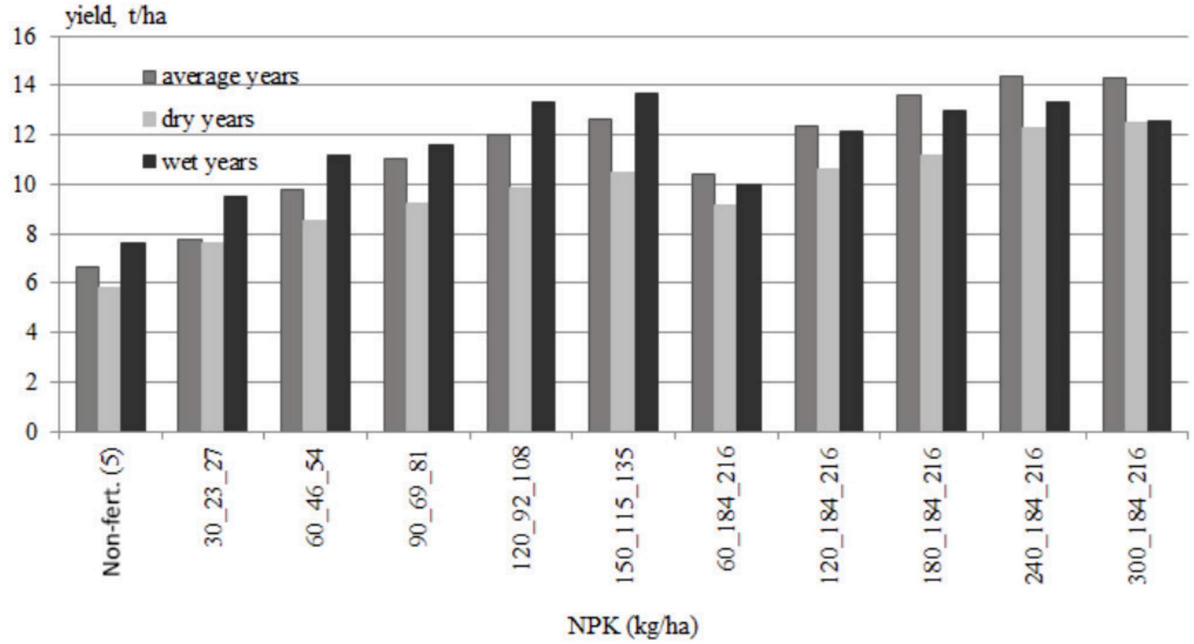


Figure 23. Effect of season (dry, average and wet) on maize yield
(Source: *Széles et al.* 2018b)

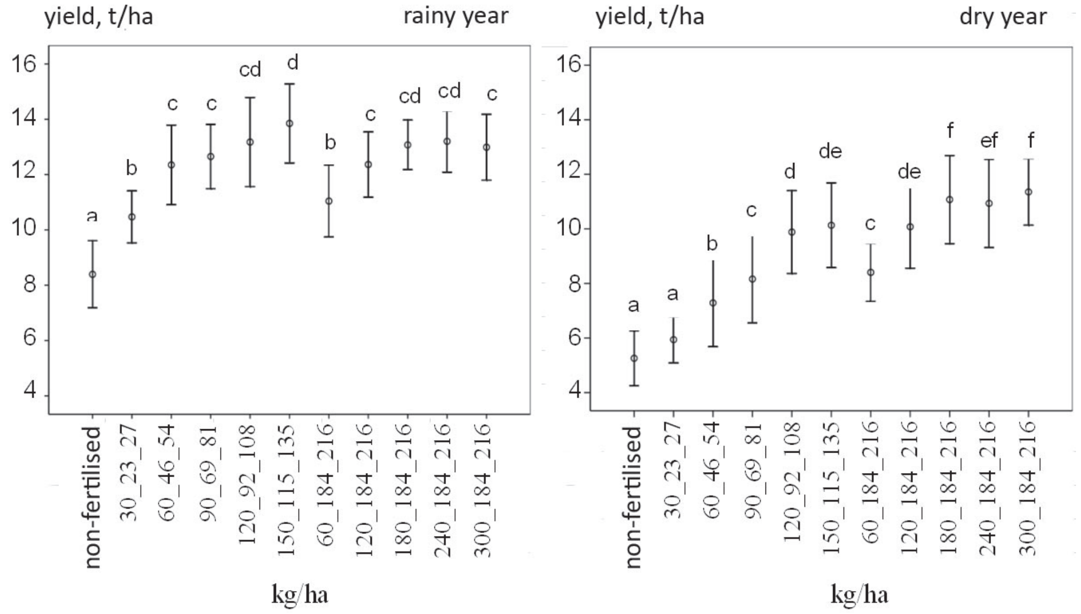


Figure 24. Effect of fertiliser application on maize hybrid yield in dry and wet years
(Source: *Széles et al.* 2018a)

Explanation: crops with different letters are significantly different at P≤0.05 probability levels according to Duncan's test

The amount of precipitation and the moisture stored in the soil also changes the fertiliser demand and the fertiliser application rate. The fertiliser application increases as the optimal water supply is approached, and then decreases when the water surplus becomes detrimental (*Szász* 1972, *Bocz* 1976, *Abramenko* 1982, *Debreczeni* and

Debreczeniné 1983, *Harmati* 1987, *Ruzsányi* 1992). Irrigation reliably increased the soil moisture content of the 40–180 cm section by about 2.5–3.0 %(m/m) in all fertilisation treatments (*Nagy et al.* 2006). No significant differences were found in the deeper soil layers between treatments (*Figure 25*).

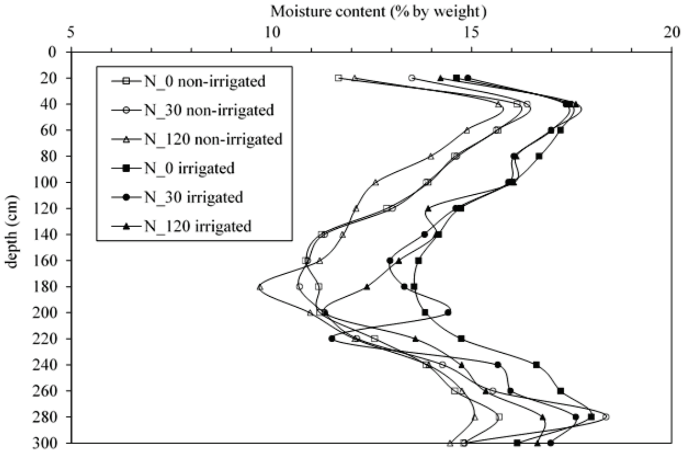


Figure 25. Effect of fertiliser application on soil moisture, Debrecen, 2002.
(Source: *Nagy et al.* 2006)

5. Fertilisation and quality

The quality of maize and its feed biological value is essentially determined by the protein and oil content of the grain, as well as its amino acid and fatty acid composition. Although the quality parameters are hereditarily determined (*Table 3*), they can be modified by ecological and agrotechnical factors (*Gundel et al.* 1981, *Kissné* 1982, *Pásztor and Kováts* 1985, *Nagy* 1997, *Gyenesné-Hegyi et al.* 2001, *Izsáki* 2006, 2009, *Hegyi* and *Berzy* 2009, *Ványiné et al.* 2011, 2012b).

The chemical composition of the yellow dent maize grain, which is the most widely grown in public cultivation, averages 70–72% carbohydrate, 8–10% protein, 4–5% oil, 3–3.5% crude fibre and 1.5–2.0% ash (*Móroczné* 2004). In southeastern Missouri (USA), on silty soils, maize grain contains 3.8–4.2% oil, 6.7%–8.9% protein, 68.0%–70.4% extractable starch and 76.0%–77.7% total starch (*Holou* and *Kindomihou* 2011).

Table 3. Maize hybrids, content composition on 100% dry matter

Hybrids	Ash (%)	Crude fibre (%)	Crude fat (%)	Starch (%)	Protein (%)
H1	1.45	3.28	3.87	73.07	10.77
H2	1.45	3.37	4.76	72.93	11.09
H3	1.45	3.87	4.66	71.64	10.78
H4	1,35	3.42	4.69	72.50	10.38
H5	1.39	3.32	4.68	71.43	11.57
H6	1.34	3.69	4.5	71.89	10.73
Average	1.41	3.49	4.54	72.24	10.89

Source: *Nagy* 1997

The feed biological value of maize protein is relatively low, because the major fractions of the protein fractions are zein (50–55%) and glutelin (30–45%), which are poor in tryptophan, lysine and methionine. The protein content of the different botanical parts of the maize grain varies considerably, with the germ containing 17–20% protein, the endosperm 7–10% and the husk 3–4%. However, in terms of mass fraction, 70–75% of the protein is concentrated in the endosperm and 20–25% in the germ. The oil content of maize grain is 2–5%, the predominant fatty acid composition is unsaturated linoleic acid 40–60% and oleic acid 25–40%. The richest in oil is the germ (30–35%) and the poorest is the endosperm (0.7–1.0%). Thus, in terms of mass, 80–85% of all lipids are found in the germ. Since the distribution of protein and oil in the eye is uneven, all the factors that change the weight of the grain, the weight ratio of the parts of the grain, affect the protein and oil content and their composition (*Izsáki* 2006).

Significant improvements in protein content can be achieved through site and hybrid selection and technology combination (*Marton et al.* 2008). The green straw (SG) hybrid has higher grain protein content and protein yield than the conventional (DD) hybrid (*Figure 26*) (*Szulc et al.* 2013).

Among the elements of cultivation technology, fertilisation, especially N supply, is the one that has the most significant impact on yield and quality. Increasing doses of N fertilisation significantly and linearly increase the crude protein content of maize grain (*Balláné* 1960, *Latkovicsné* 1961, *Krámer* and *Pekáry* 1962, *Lőrincz* 1969, *Szirtes* 1970, *Veress* 1973, *Bocz* and *Pekáry* 1974, *Gagro* 1974, *Lásztity* 1975, *Sarkadi* 1975). The magnitude of the increase is between 5 and 39% depending on the crop year. The highest crude protein content, however, is obtained under non-irrigated conditions with NP and NPK fertilisers (*Latkovicsné* 1961, *Krámer* 1966, *Bocz* 1976). P fertilisation did not affect the quality of maize grain (protein and oil content, fatty acid composition) in the range of 120–340 mg/kg AL-P O_{25} , K fertilisation in the range of 205–465 mg/kg AL-K_2 O supply of the cultivated soil layer (*Izsáki* 2006).

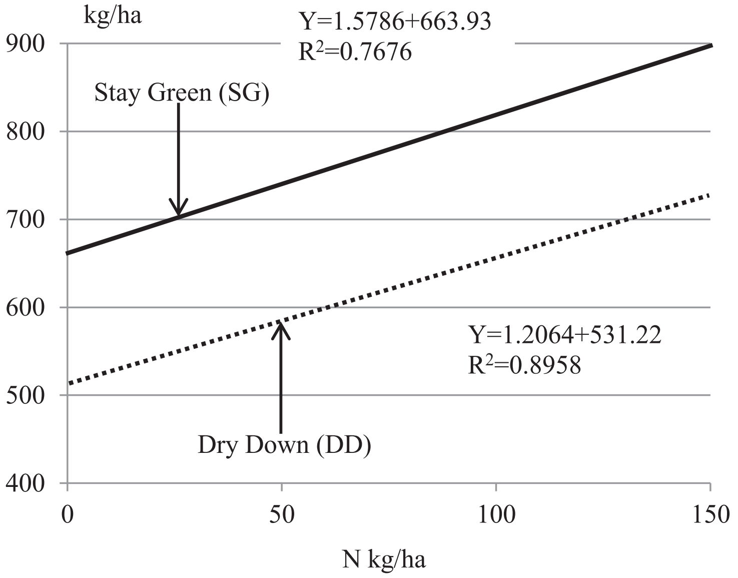


Figure 26. Effect of N fertiliser
on protein yield of maize hybrids with different genotypes
(Source: *Szulc et al.* 2013)

According to *Győrffy* (1965), N fertilisation also increases the protein content of maize, but does not improve the protein quality, because it increases the proportion of less valuable amino acids. *Radulov et al.* (2010) showed that maize yield increases resulted in lower protein concentrations, except when the yield increase resulted from N fertiliser application. The higher nitrogen content altered the amino acid balance, thus reducing the nutritional value.

According to *Bocz* and *Pekáry* (1974), *Muszijko et al.* (1961), *Bocz* (1976) and *Szirtes et al.* (1977), the crude protein content of grain yields is also significantly influenced by weather. This variation is closely related to the variation in yield. A weakly negative linear relationship between maize yield average and crude protein content (*Bhatia* and *Rabson* 1987, *Sander et al.* 1987) and a strongly positive linear relationship between yield average and crude protein yield is reported by *Kralovánszky* (1975) and *Bálint* (1977). In the experiments of *Getmanets* and *Klyavzo* (1981) in Ukraine, the protein content of maize grain also increased with increasing N doses in chernozem soils. The amino acid composition, however, also showed an unfavourable change. Zein increased, lysine and tryptophan decreased. The results of *Izsáki* (2006) in his fertilisation duration experiments in Szarvas showed that the protein content of the grain was only related to N fertilisation. Increasing N supply resulted in higher protein content, but above 80 kg N/ha the increase in protein content was not significant. In a cooler growing season with better water supply (2001), protein content was lower (8.4–10.2%) than in a drier, warmer growing season (2002), when protein content ranged between 11.17–12.87%. On chernozem meadow soils with a humus content of nearly 3%, whose annual N supply without N fertilisation averages about 100–120 kg/ha over 15 years, N fertilisation of 80 kg/ha can achieve grain yields close to the yield maximum, favourable protein and oil contents, and amino acid and fatty acid composition, which are not significantly higher in yield and quality with higher N fertilisation rates.

The high protein content of maize grain was ensured by NPK treatments with higher nitrogen content. Fertiliser treatments with 150 kg/ha nitrogen resulted in a protein level that can be considered optimal under the given conditions (*Szulc et al.* 2013, *Széles et al.* 2018b) (*Figure 27*). The five genetically distinct hybrids H1 (FAO 320), H2 (FAO 340), H3 (FAO 380), H4 (FAO 420) and H5 (FAO 490) responded differently to the crop year modifying effect of protein content. The highest protein content of hybrid H5 (FAO 490) was provided by the treatment combination 150:115:135 ($P<0.05$), regardless of the season, while for hybrid H3 (FAO 380) it was provided by the treatment combination 120:92:108 kg NPK ha^{-1} ($P<0.05$). For hybrids with H4 (FAO 420), H2 (FAO 340) and H1 (FAO 320) maturity, lower treatment combinations in a favourable water year and higher treatment combinations in an unfavourable year resulted in the highest protein content (*Széles et al.* 2019b).

As the N ratio increased, the oil and starch content of maize grain decreased, while protein content and protein, starch and oil yields increased, reaching a maximum value corresponding to 179.0 kg N/ha (*Holou* and *Kindomihou* 2011).

Lower protein content in wet years and higher protein content in dry years are reported in the literature (*Szirtes et al.* 1977, *Szániel et al.* 1980, *Lilburn et al.* 1991, *Győri* and *Sipos* 2005), with the influence of the heat unit, the amount and distribution of precipitation in June, July and August being particularly important (*Asghari* and *Hanson* 1984). At higher water availability levels (which can be provided by rainfall or irrigation), a reduction in protein content can be expected, which can be corrected by adequate nutrient supply and a significantly higher yield can be achieved (*Debreczeni* 1964, 1965, *Debreczeniné* 1965, *Teresenko* and *Zsabickij* 1973, *Ruzsányi* 1977) *Győri* 1978, *Győri* and *Sipos* 2005).

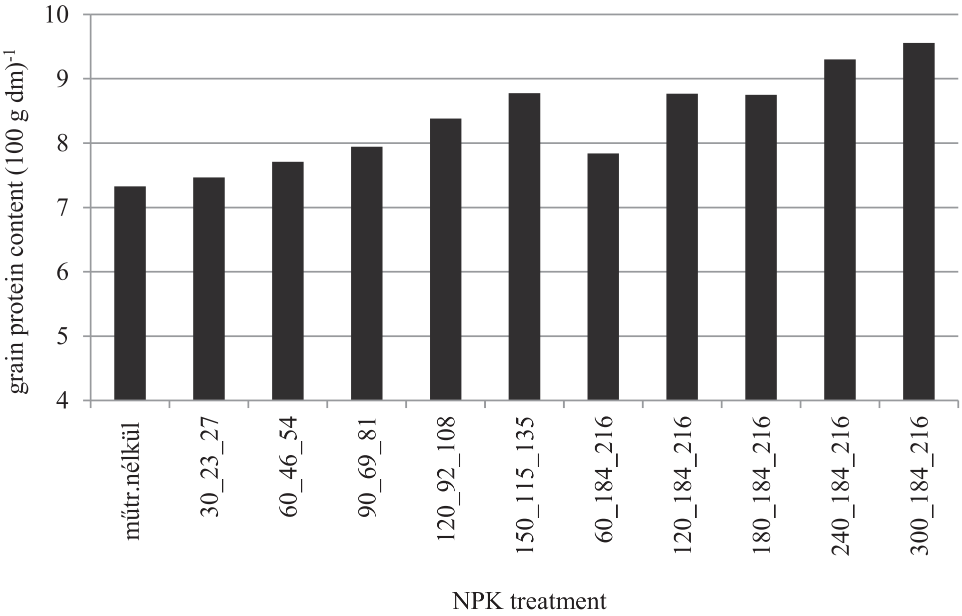


Figure 27. Effect of fertilisation on the protein content of maize grain
(Source: *Széles et al.* 2018b)

The amount of nitrogen and the type of nitrogen fertiliser used significantly affected protein content and yield. Slow-release nitrogen fertilisers, such as ammonia sulfate and urea, had a significantly greater effect on protein yield than slow-release nitrogen fertilisers. Protein content of maize grain was significantly modified by the interaction of nitrogen fertiliser type and maize genotype (*Szulc et al.* 2013).

The phosphorus content of maize grain increases only slightly with phosphorus fertilisation (*Balláné* 1960, 1963, *Pekáry* 1969, *Prohászka* and *Cserni* 1969, *Szirtes* 1970, 1971, *Bocz* and *Pekáry* 1974, *Latkovicsné* 1975, *Bocz* 1976, *Győri* 1998). In some experiments, the phosphorus content remained unchanged (*Balláné* 1962, *Prohászka* and *Gurabi* 1972, *Lásztity* 1975, 1976).

According to *Debreczeni* (1964, 1965) and *Ruzsányi* (1975), the phosphorus uptake of maize increases with both fertilisation and improved water supply, but the higher dry matter weight crop shows some dilution in nutrient content. The phosphorus content of maize grain increases slightly with irrigation, i.e. with improved water supply, while the potassium content remains unchanged.

After nitrogen, phosphorus and potassium, sulphur is the fourth most abundant constituent of plant organisms. In addition to its effect on yield, it also influences quality by regulating the levels of sulphur-containing amino acids. *Allen* (1979) and *Salunkhe et al.* (1985) determined the sulphur content of maize grain at an average of 1400 mg/kg, which, according to *Tölgyesi* (1991), is increased by phosphorus, calcium and sulphur fertilisation. *Győri* and *Sipos* (2005) determined the sulphur content associated with critical phenophases, which may be helpful in assessing the adequate sulphur supply.

They found that the sulphur content decreases gradually with plant age; five-leaf maize contains on average 2000–4000 mg/kg, ten-leaf maize 700–3000 mg/kg, while at maturity only 1000 mg/kg can be detected in the leaves and 600–700 mg/kg in the stalk. Excess water supply can lead to a slight sulphur deficiency, which can be avoided by appropriate basal fertilisation (superphosphate) or corrected by foliar fertilisation, based on tests at critical phenophases.

Based on the results of experiments conducted by *Nagy* (1987), it was found that fertilisation increased the N, P, K, Mg, Mn, stalk P, K, leaf N, P, K, Cu, Mn, Fe, ear N, Mn, Fe and ear Fe contents in both non-irrigated and irrigated treatments while decreased the content of Mg, Zn, Mn, Fe in stem, Mg, Zn in leaf, P, K, Mg, Zn, Cu in the husk leaves and N, K, Mg and Zn in the cob. No changes were observed in the Fe content of the grain, and the P and Ca contents of the cob. Irrigation decreased the N and K content of the grain and increased the P content (*Figure 28*).

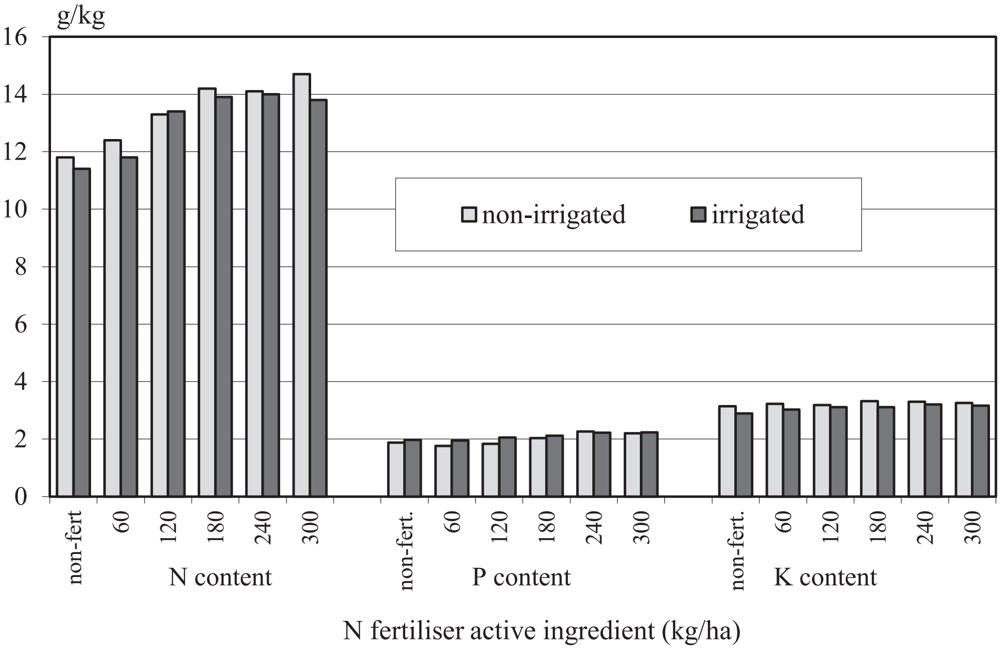


Figure 28. Effect of fertilisation
and irrigation on the N, P and K content of maize grain yield
(Source: *Nagy* 1987)

6. Supplementary fertilisation

Phosphorus reserves that can be mobilised from the maize grain are quickly depleted by the time the maize is 2–4 leaves old. The micro-granulated *starter fertiliser,* applied to the seed in one pass with sowing, provides the nutrients most needed for juvenile development, especially easily absorbable phosphorus, at the most critical stage of plant development, the early vegetative stage (emergence, V1-V5), especially in cold and wet spring soil conditions. This ensures uniform germination and vigorous root growth (*Grath* and *Binford* 2012, *Quinn et al.* 2020). The commonly used micro-granular starter fertiliser rates are 15–20 kg/ha but, in cold, high plasticity soils, 20–25 kg per hectare may be justified. Without starter fertilisation, the development of the crop will be stunted (*Hoffmann* 2016). However, with starter fertilisation, the initial development of the plant is more favourable, the maize plant yields more intensively and flowers earlier, based on good nutrient supply. The time gained by better nutrient supply is often not marked, but in a given situation the 1–3 days gained by earlier flowering maize can also avoid the yield-reducing effects of high temperature, dry periods (Árendás 2016). On average, starter fertilisation increased maize yield by 5.2%, but the resulting yield advantage decreases as plant density increases (*Quinn et al.* 2020).

In order to achieve high yields, plants cannot always obtain sufficient micronutrients from the soil, i.e. foliar fertilisation has become an indispensable technological element (*Kádár* 2002). The uptake of some nutrients through foliar application can be 2–20 times more efficient than through the roots from the soil. However, there are serious limitations in the amount of nutrients that can be absorbed, so the supplementation of micronutrients and, in critical cases, some macronutrients such as magnesium or sulphur, through foliar application is justified (*Hoffmann et al.* 2014).

The effectiveness of basal and foliar fertilisation can be enhanced by biostimulants, which are extracts of organic materials containing bioactive ingredients. They improve the efficiency of root nutrition, for example as a result of increased cation exchange capacity of the soil, thus allowing for increased uptake of macro- and micro-nutrients. They also improve phosphorus uptake, due to their effect on calcium phosphate precipitation (*Hoffman* 2018).

Various macroalgae and microalgae are sources of organic biostimulant compounds that aid plant life processes (*Arioli et al.* 2015). The application of macroalgae-containing biostimulant foliar fertiliser, mostly extracted from the sea, increases maize green weight and grain yield *Basavaraja et al.* (2018), but uniformity of raw material quality is greatly influenced by age, environmental conditions, available nutrients and harvest date (*Marsham et al.* 2007). Microalgae have the advantage of uniformity of raw material quality and more cost-effective production (*Barone et al.* 2019). The use of microalgae as plant biostimulants can influence cellular respiration, photosynthesis, nucleic acid synthesis and ion uptake by plants, as well as improve the availability of soil nutrient reserves to plants, increase soil water holding capacity, plant antioxidant status, increase cell metabolism and chlorophyll content (*Blunden et al.* 1996, *Bulgari et al.* 2015, *Crouch* and *Van Staden* 1993, Ördög 2015). *Chlorella spp., Dunaliella spp., Nostoc spp.* and *Aphanizomenon spp.* microalgae species are produced in the largest quantities. The microalgae biomass extracted from them contains macro- and microelements and can be considered as organic slow release fertilisers due to their NPK content (*Coppens et al.* 2016).

There are three main methods of agricultural application of microalgae: as a suspended liquid soil amendment algae formulation using appropriate carriers; as a dry granular or powdered soil amendment biomass; or as a foliar application of extracted algal cultures, with appropriate concentration and spray rate (*Renuka et al.* 2018). The latter has been shown to be the most effective in terms of biostimulant effect, as at high relative humidity, the permeability of the leaf through its open stomata is increased, allowing the plant to take up large amounts (*Chiaiese et al.* 2018).

The use of microalgae and cyanobacteria as biofertilisers can result in higher biomass accumulation and consequently higher yields (*Garcia – Gonzalez* and *Sommerfeld*

2016, *Shaaban et al.* 2001). Plant treatment with 0.1% *Nostoc piscinale* biomass positively affected the growth, development and consequently the yield of the sunflower test crop (*Pőthe et al.* 2013). *Illés et al.* (2020) applied *Nostoc piscinale* biostimulant foliar fertiliser (at a concentration of 0.3 g*l^{-1} and 1 g*l^{-1} applied with 400 l*ha^{-1} of water and the addition of an ethoxylated isodecyl alcohol active adhesion enhancer formulation) to maize at the 8-leaf development stage. The 0.3 g*l^{-1} foliar fertiliser treatment increased the yield by 10% and the 1 g*l^{-1} treatment increased the yield by 11% (*Figure 29*). The algae treatment increased the protein content of the grain yield by more than 6% (*Figure 30)*. During the growing season, the algae treatment increased the proline content of the green parts of the plant, which had a positive effect on the maize's defence system against drought stress.

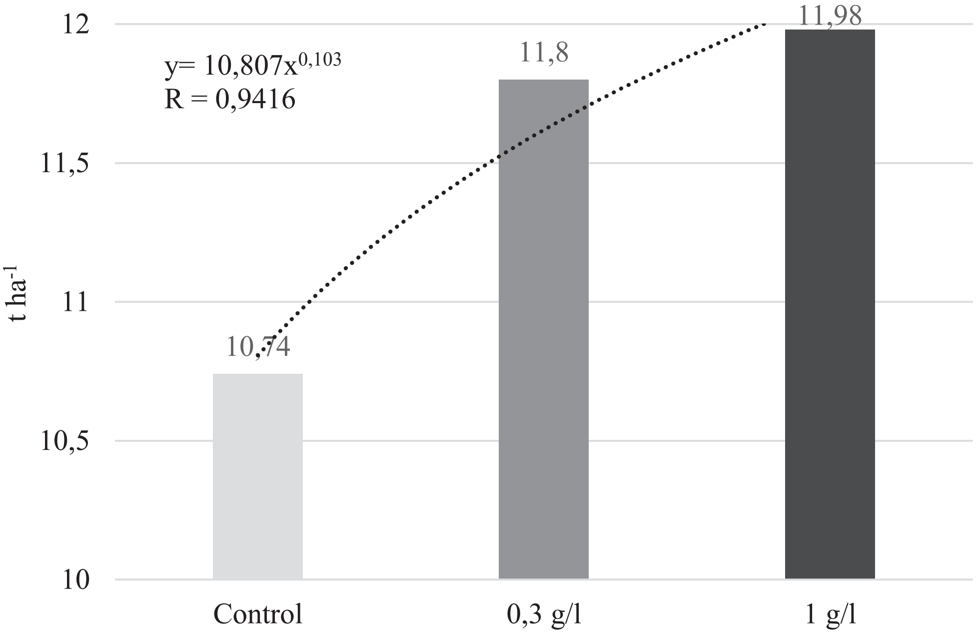


Figure 29. Effect of *Nostoc piscinale* foliar fertiliser treatment on maize yield
(Source: *Illés et al.* 2020)

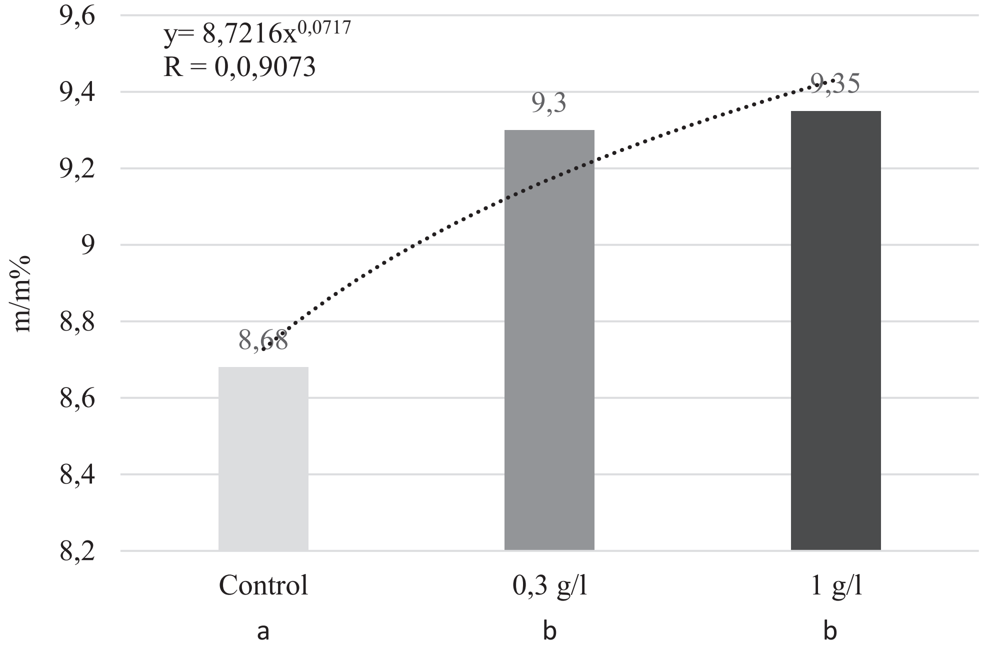


Figure 30. Effect of *Nostoc piscinale* leaf fertiliser treatment on grain protein content (Source: *Illés et al.* 2020)

7. Nutrient supply and methods

7.1 Timing of nutrient supply according to plant development

The optimum time to apply nitrogen is in the spring (*Timmons* and *Cruse* 1990), but some of the N applied at high rates before sowing may volatilise or leach out. This is because poorly developed root systems have less access to soil reserves early in plant development (*Alley et al.* 2009). The application of adequate amounts of spring base and top dressing reduces N losses (*Kalocsai et al.* 2004a), increases the efficiency of nitrogen supply, improves the economics of nutrient supply and yield, and increases production efficiency (*Tóth* 2002, *Csathó* 2003, *Muthukumar et al.* 2007, *Sitthaphanit et al.* 2010, *Széles et al.* 2019a).

Overall, top dressing is an agro-technical tool that increases the efficiency of crop nutrition and has a major impact on the quantity and quality of the crop. However, it involves additional operational costs, and therefore its necessity and, if necessary, the number of divided doses of nutrients to be applied must be decided in relation to its yield (*Tóth* 2002, *Széles et al.* 2019b).

Planning N fertilisation during the higher N demand period, which lasts from the intensive stem growth period to the drying of the stems and requires 85% of the total nitrogen requirement of the crop, is essential to optimise yields (Árendás 2016) and reduce the cost of nitrogen application. The earlier maturity and higher yield potential of current hybrids increases the nitrogen demand of maize, especially in the most advanced growth stages of the crop (*Sangoi et al.* 2016). *Ciampitt* and *Vyn* (2013) showed that modern maize hybrids take up 29% more nitrogen after flowering than older hybrids. The same was found by *Haegele et al.* (2013), who compared 1970s hybrids with modern hybrids and observed that current hybrids accumulated 40% more N after flowering and uptake 8.96 kg/ha more nitrogen over their cycle. Such traits increase the benefits of nitrogen sharing.

Experiments to determine the time and amount of nitrogen release were carried out by *Gross et al.* (2006). Four N fertiliser treatments were applied: 40 kg/ha N pre-sowing and without nitrogen top-dressing; 40 kg/ha N pre-sowing+120 kg/ha shortly after sowing; 40 kg/ha N pre-sowing+60 kg N/ha at stages V4-V5+60 kg N/ha at stages V7-V8; 40 kg/ha N pre-sowing+120 kg N/ha at stages V6-V7. The 40 kg/ha N pre-sowing and without nitrogen top dressing and the 40 kg/ha N pre-sowing+120 kg/ha shortly after planting nitrogen fertilisation treatments affected plant height, ear height and significantly increased maize yield (*Gross et al.* 2006).

Splitting nitrogen into two (1/2 N at V5 and 1/2 at V10) or three (1/3 N at V5, 1/3 at V10 and 1/3 at VT) applications did not increase maize yield and agronomic N use efficiency compared to fertilisation with a single high N application at the V5 or V10 phenophases (*Panison et al.* 2019). Late top dressing rates (V12) did not cause yield reduction and resulted in higher NUE. Nitrogen dose-splitting resulted in better NUE than combinations in which no nitrogen was applied at seeding or top dressing (*Amado* 2017).

Top dressing up to the V12 phenological phase is a good strategy to optimise yields and reduce nitrate loss, but application after the V12 phenophase causes yield loss (*Binder* et al 2000, *Jaynes* and *Colvin* 2006, *Ruiz Diaz et al.* 2008).

For profitable maize production, 225 kg/ha N fertiliser rate is applied in three equal rates (1/3 at sowing + 1/3 at V8-10 + 1/3 at tasselling) *(Sharifi* 2016), while *Zhong et al.* (2014) recommend 242 kg/ha N rate applied in two stages (30% at sowing and 70% at tasselling until 80–10 leaf stage).

Splitting the N-rate (pre-sowing and 4–6 leaf stage) in maize results in a yield gain of 0.5–1.0 t/ha. N-sharing is determined by pre-sowing and stem residue management (*Kismányoky* 2014), weather and genotype (*Széles et al.* 2019a). More efficient uptake and better utilisation were achieved in a rainy year with the application of 60 kg N/ha spring base + V6 phenology stage +30 kg N/ha ($V6_{90}$) top dressing in both the FAO 490 and FAO 320 hybrids. In what can be considered an average year, top dressing application did not result in reliable additional yields in the case of the FAO 490 hybrid, and the basic treatment of 120 kg N/ha proved to be effective. For the FAO 320 hybrid, an early application of top-dressing ($V6_{150}$) at a spring basal rate of 120 kg N/ha was more beneficial (*Figure 31*) (*Széles et al.* 2019a).

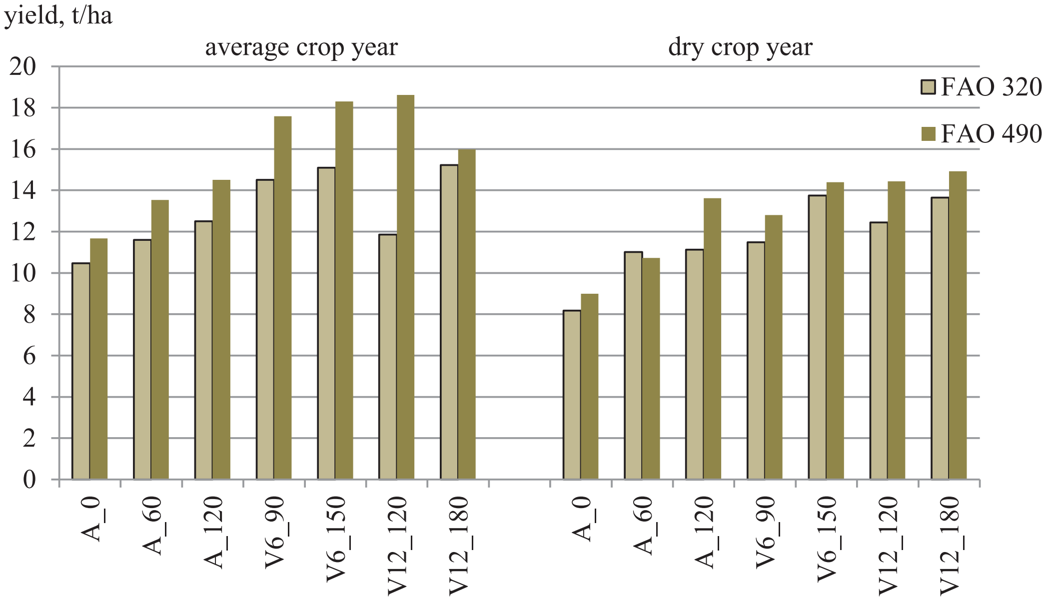


Figure 31. Effect of N-base and top dressing on yield of maize hybrids
(Source: *Széles et al.* 2019a)

Foliar feeding is a new technology in modern plant production that has a direct effect on plant physiology. Timing is crucial, rapid and effective intervention can avoid yield loss or quality deterioration, but their use under favourable conditions can increase yield and improve quality (*Hoffmann et al.* 2014). The spring-summer application and timing of foliar fertilisers to supplement solid and liquid fertilisers and micro-nutrients should only be based on the results of professional soil and, if necessary, plant laboratory tests (Árendás 2014). If a deficiency of a micro-nutrient is clearly expected from the results of soil tests or from deficiency symptoms observed in the previous crop, it is worth including 1–3 foliar fertilisers in the technology. The earliest time is 2–4 leaf stage (this is the period when the ear length is determined), at which time it is worth using in-line spraying to reduce losses. This can be followed by the 6–10 leaf period. The third application should only be done with a tall tractor before tasselling (*Hoffmann* 2016).

In the V5 phenophase of maize, the application of zinc foliar fertiliser increased yields by 18% (three-year average) compared to NPK alone. Crops treated with 1.0 kg Zn/ha significantly increased total N uptake and grain yield. Zn treatment had the largest effect on grain number per plant (17.8%) and at the same time the largest dependence on N uptake (R2 = 0.79) (*Potarzycki* and *Grzebisz* 2009).

Depending on maize fertilisation, nitrogen and chelated zinc (6 leaf) and zinc monometal chelate (10 leaf) applied in two rounds at higher fertilisation rates increased yields by 0.7–1 t/ha. Maize responded well to the applied iron and boron foliar fertilisers. The yield increase was 1.5–1.7 t/ha. The application of boron also increases yield in maize, so its use as foliar fertiliser is definitely perspective (*Hoffmann et al.* 2018).

In the V6 phenophase of maize, there was a linear decrease in plant height and first ear height with increasing doses of Cu foliar fertiliser. Chlorophyll content, leaf area, diameter and length of the tube, thousandths of grain weight and yield increased at doses up to 100 g/ha Cu, but higher doses resulted in a decrease. Therefore, application of foliar Cu fertiliser at doses higher than 100 g/ha showed toxic effects in maize plants, with reduction in growth and yield (*Barbosa et al.* 2013).

7.2. Methods of nutrient supply

There is a long-standing and constant need in agricultural practice to develop nutrient management techniques based on a reliable and accurate method that takes into account the plant and its environmental factors, as inappropriate nutrient supply is a problem.

In Hungary, the first advisory system taking into account the properties of the plant and the soil was established at the end of the last century by the National Hungarian Royal Institute of Chemistry. Its leader, *Liebermann* (1886), drew two conclusions that are still valid today on the basis of his numerous experiments with fertilisation in large plots:

– the primary role of nutrient replenishment is to meet the needs of the plant,
– the effect of fertilisation is always determined by its economic efficiency.

Liebermann (1895) was also the first to publish his soil-strength recovery system based on soil tests.

When determining the amount of fertiliser to be applied, two basic relationships should be borne in mind. One of these is Liebig's „minimum law" and the other is the principle of diminishing marginal returns.

Today, researchers, institutes and university departments around the world are working to develop nutrient management systems that best serve agricultural production under the natural economic conditions of a given country or region. In Hungary, Antal, Sváb, Sipos and Nagy started to develop a new nutrient supply method in 1974, using computer processing of field data from state farms. The work continued to be developed within the framework of the MÉM NAK, and fertilisation guidelines and an operational calculation method for fertilisation were drawn up with the involvement of the country's leading researchers and specialists (*Debreczeni* 1979, *Antal* 1983). The specialists tried to take into account both the nutritional and environmental factors of the plants. According to this method, the soil must be chosen correctly in order to grow crops effectively.

Several successfully applied soil recharge systems have been reported in the literature. National and foreign experts suggest to evaluate the effect of fertilisation on the basis of the results of soil fertility experiments (*Tisdale* and *Nelson* 1966, *Kováts* 1981, *Pető* 1990, *Pummer* and *Holló* 1991, *Lewis* 1993, *Debreczeni* and *Debreczeniné* 1994, *Kádár* and *Szemes* 1994, *Lengh* and *Johnston* 1994). *Rod* and *Ryser* (1969) describe the Dirks-Schaffer method of soil fertility determination used in Switzerland and its applicability. They classify soils into fertilisation categories according to the nutrient content, based on index numbers, and determine the rate of fertilisation in accordance with the planned yield and the amount of nutrients that can be extracted. *Ansorge et al.* (1971) used a computer to determine the amount of fertiliser and the time of application based on 12 site groups and 53 crops. According to *Nelson* (1972), a nutrient application method based on plant analysis and soil testing was successfully applied in New York State. The soil amendment system developed by *Rudeforth* and *Webster* (1973) consists of recording the results of soil analysis and developing a programme to match the nutrient requirements of each crop to the data from a genetic soil map.

Already *Mitscherlich* (1952) stated that fertilisation advice can only be based on field trials, because laboratory tests can be misleading. Nor did *Kreybig* (1955) consider nutrient supplementation based on soil tests alone to be sufficient. He also recommends the incorporation of empirical methods based on field books. *Viets* and *Hanway* (1957) in Fort Collins, Colorado, found that reliable nutrient replenishment could only be based on long-term experiments adapted to crop species. *Hera* and *Triboi* (1971) investigated the mathematical laws of nutrient recycling. They found that local economic, empirical factors are at least as important as specific soil, environmental, etc. test results. *Grass* (1972) carried out experiments on several farms in Germany, comparing the effects of fertilisers calculated and applied on the basis of soil tests and the effects of local empirically applied fertilisation methods. In his opinion, the soil tests provide a useful guide to nutrient replenishment, but are not sufficient in themselves. The use of nutrients will ultimately be decided by the practitioner, taking into account the results of the research, but mainly on the basis of the economic outcome that the method can achieve.

According to *Dezső* (1976), the various methods of fertiliser dosage do not take sufficient account of the natural fertility of the soil. He suggests the use of his model, where the fertiliser yield curves are based on soil quality. The functions can and should be used to determine the optimum utilisation of fertiliser rates for each crop. A common feature of the nutrient management systems listed is that their scientific and, above all, technical sophistication has not yet been sufficient to produce an accurate and fully reliable fertilisation advice. This problem is certainly due to the fact that the nutrient requirements of the crop, the mechanisms of nutrient uptake, the nutrient supply capacity of the soil, the effects of tillage and the way in which nutrients are applied were known in principle, but the interrelationships between them were not yet sufficiently understood.

Sarkadi (1975), based on his own studies and on literature sources, analysing the average NPK contents calculated from the mean values of nutrient content tests carried out in different periods and in different countries, found that the data varied considerably. Opinions also differed as to the fate of nutrients released to the soil. According to *Lőrincz* (1980), the effects of P and K fertilisation persist for many years. *Minejev et al.* (1980) found that in the second year after fertilisation N is available in 10%, P O_{25} in 8–10% and K_2 O in 10–15%.

According to *Russell* (1970), the way forward in nutrient management is to use liquid fertilisers and to increase the active ingredient content of fertilisers, while *Csizmazia* (1990) considers uniformity of application, fertiliser application rate, active ingredient and quality as important factors for successful nutrient management.

In Hungary, in the last 15–20 years, teachers and researchers at all three Universities of Agricultural Sciences, the research institutes of the universities, the Agricultural, Soil and Agrochemical Institutes of the ELKH ATK, as well as at the Grain Research Ltd. and its predecessor institutions have contributed significantly to the knowledge of the principles of plant nutrition and the practical application of professional methods. The question of determining the optimum level of fertilisation required for the nutrient supply of a given plant species, including the variety/hybrid, is a matter of concern to many researchers (*Arnon* 1975, *Antal* 1983, *Buzás* 1983, *Nagy* 1986, *Sárvári* 1986, *Csathó et al.* 1989, *Debreczeniné* 1989, *Krisztián et al.* 1989, *Debreczeni* and *Debreczeniné* 1994, *Széll* 1994). This question has several components. First, the soil-plant relationship. Even if one disregards the nutrient supply capacity of the soil and looks only from the fertiliser application side, the nutrient binding capacity of the soil has to be taken into account. On the other hand, the nutrient uptake and utilisation properties of the plant must also be taken into consideration.

The nutrient requirements of the expected crop, taking into account the nutrient sources already available in the soil and the expected nutrient losses, are adjusted in such a way that the nutrient content of the soil is not reduced (*Sarkadi* 1975, *Lásztity* and *Kádár* 1978, *Bocz et al.* 1979, *Debreczeni* 1979, *Latkovics* 1979, *Láng* and *Németh* 1979, *Jolánkai* 1985, *Lásztity* 1989, *Balláné* 1991, *Kádár* 1992, *Németh* 1993).

Compared to the MÉM NAK method, a novel, cost- and environmentally friendly MTA TAKI–MTA MGKI (*Csathó et al.* 1998a,b) fertilisation advisory system was developed. The philosophy and fertiliser dose recommendations of the system were compared with the previous intensive (MÉM NAK 1979) system (*Table 4*). The recommendations of the cost and environmentally friendly fertilisation system are based on the correlations obtained from the database of domestic field fertilisation trials, the recommended fertiliser rates are applied at the lowest possible rates to achieve safe production and high yield levels.

According to *Győri* (1984), the calculation of fertiliser dosages should be based on the liquid phase of the soil rather than on the soil volume and its salt concentration. According to his findings, taking into account a 0–30% fixation, the upper limit of fertiliser doses can be 0.6–1 t/ha.

Berzsenyi and *Győrffy* (1996) are of the opinion that manure application and return of crop residues (maize stover, wheat straw) with NPK supplementation is an effective method of fertilising maize.

Table 4. Comparison of the philosophy of intensive nutrient supply and environmentally friendly fertilisation advisory systems

Intensive nutrient supply system (GERMANY NAK 1979)	Environmentally friendly fertilisation system (MTA TAKI – MTA MGKI)
Aiming for *maximum* yield	Striving for *economic* yield levels
The aim is to *"fertilise the soil"*	The aim is to *"fertilise the plant"*
Achieve and maintain a *good to very good* soil PK supply	Achieve and maintain *medium to good* soil PK coverage
Quick soil PK refill	*Slow* soil PK-filling
PK fertilisation *every year*	PK fertilisation of *crop rotation* (periodic PK fertilisation)
PK fertilisation for *all* soil PK coverage levels	PK fertilisation only in soils with *good to medium* PK *and below*
Higher soil nutrient limits	*Smaller* soil nutrient limits
Uniform soil nutrient limits	*Plant group-dependent* soil nutrient limits
Higher specific nutrient contents	*Lower* specific nutrient contents
Specific nutrient contents *independent of the planned yield*	Specific nutrient contents depending on the *planned yield*

Source: *Csathó et al.* 2003

Analyses to calculate nitrogen fertiliser recommendations are time-consuming and costly. The use of optical sensors is increasing to detect nitrogen (N) deficiencies and to determine fertiliser doses during the growing season. Nitrogen deficiencies are difficult to detect early in the growing season. Both NDVI and SPAD can detect N deficiency in the early growing stages. The combination of leaf N, SPAD and NDVI data can become a tool to manage the nitrogen status of maize fields and to calculate maize yield (*Yadava* 1986, *Piekielek* and *Fox* 1992, *Feil et al.* 1997, *Berzsenyi* and *Dang* 2001, *Széles* 2008, *Bushong et al.* 2018, *Edalat et al.* 2019).

8. Environmental aspects of fertilisation, technical advice

Agricultural activity has an impact on the environment, the nature and extent of which has varied considerably throughout history. The greatest changes in the environment occurred when crop production became intensive with the mechanisation of crop production, the use of intensive cultivation methods and the use of chemicals. In Hungary, the intensive phase of crop production was characterised by increasing yields, a disregard for quality requirements, and the increasing use of energy carriers, industrial materials, machinery and equipment. After the political restructuring, financial difficulties, unresolved land tenure issues, ageing of agricultural machinery and equipment led to a decline in crop production and the use of industrial inputs. Both periods triggered damaging processes in both crop production and environmental protection (*Ruzsányi* and *Pepó* 1999).

One-sided land use has resulted in a deterioration of the physical condition of soils, their water holding capacity and water retention capacity, and an increased risk of inland flooding. In some areas, soil acidification has been observed, resulting in slower nutrient uptake, reduced nutrient uptake and reduced nutrient supply capacity (*Ruzsányi* and *Pepó* 1999), while in other areas, soil nitrogen concentrations have increased and nutrient ratios have become unbalanced (*Loch* 1999a).

The aim of crop production is to achieve high yields and high quality. To achieve this objective, it is necessary to use organic and inorganic nutrients, but inappropriate nutrient supplementation can damage the environment (*Szabó* 1999, *Sloan et al.* 1999, *Nagy* 2007, 2012). The implementation of sustainable farming principles has become an important objective. The concept of sustainability has been defined by several authors, all of whom emphasise the protection of natural resources. Sustainable farming requires that, in addition to economical aspects, ecological aspects should also be taken into account, and that economic production should be achieved while taking account of the specific conditions of the production area and with the least possible impact on the environment. Sustainable development also requires ecological considerations in nutrient management in order to ensure that nutrient supply can be achieved with minimum environmental impact (*Loch* 1999a).

With 85.5% of Hungary's total land area under agricultural production, environmental protection is highly dependent on agriculture. The efficiency of agricultural production depends on the quality and condition of the environment and natural resources, so environmental degradation can lead to a deterioration in production results. Hence the interdependence of environmental protection and agriculture, and the need to coordinate these two areas (*Pepó* 1999).

The impact of manure on the environment. During the storage of manure, organic matter and nitrogen losses can be as high as 30–60%, while phosphorus and potassium levels are only slightly reduced. During the maturation of manure, gases are produced (CO_2, NH_4) that enhance the greenhouse effect, play a role in acid rain (*Szabó* 1999, *Bourke et al.* 2019) and have a detrimental effect on the stratospheric ozone layer (*Galloway* and *Cowling* 2002). Soluble nitrogen compounds can leach into groundwater when excessive amounts of manure are applied, can leach some of the potassium in sandy soils (*Szabó* 1999), can acidify soils, can cause changes in the biodiversity of ecosystems (*Peoples et al.* 2004) and can pose risks to human health (*Fan* and *Steinberg* 1996, *Gulis et al.* 2002, *Yang et al.* 2007).

Effect of slurry on soil. Application of slurry positively affects soil fertility (*Biró et al.* 2015) by increasing pH and the availability of P, K and Mg without affecting organic C and total N (*Duffková et al.* 2015), and it also affects soil structure (*Hassink et al. 1997, Evanylo et al. 2008, Balázsy* and *Sárdi* 2011). Soils over-irrigated with slurry can become more compacted as colloidal-sized components can block capillary passages. On the other hand, micro-nutrients may accumulate in the soil and enter the animal's body in higher amounts through feed supplements. The slurry has a high Na content, so upward water movement can lead to salinisation when soil water is high. Excessive use of slurry can also lead to waterlogging and siltation of the treated area, and the development of anaerobic conditions can lead to reductive processes, which result in the accumulation of substances harmful to plants (*Szabóné* 1976, *Szabó* 1999). The accumulation of NO_3 -N and the leaching of Ca ions leads to soil acidification (*Stefanovits* 1977, *Szabó* 1999).

Impact of slurry on groundwater and natural waters. Slurry has a high nutrient content, which can enter natural waters, rivers and lakes through groundwater. A sudden increase in the nutrient content of the water triggers eutrophication processes, the oxygen content of the water decreases and the gases produced by the decomposition of nutrients can cause fish mortality (*Stefanovits* 1977, *Szabó* 1999). Nitrate can enter groundwater, degrade its quality and render the water from wells deposited on it undrinkable, because it can cause methemoglobinemia (*Szabó* 1999, *Huertas et al.* 2016), hypertension, infant mortality, gastric cancer, thyroid disorders, cytogenetic abnormalities and birth defects (*Höring* and *Chapman* 2004). Slurry may introduce bacteria (*Salmonella, E.coli*), viruses and parasites into soil, groundwater and natural waters, which may vary in species and numbers depending on the species, husbandry, manure storage and duration of the animal (*Stefanovits* 1977, *Szabó* 1999, *Sommer et al.* 2013). Pathogens can remain virulent for a certain period of time and epidemics may develop. Enteroviruses and human parasite eggs can be released into the environment with dilute pig manure (*Szabó* 1999).

The effect of slurry on the air. Some of the gases released from slurry cause unpleasant odours. These include ammonia, hydrogen sulphide and mercaptan (*Szabó* 1999, *Rzeźnik* and *Mielcarek-Bocheńska* 2020). Among the gases produced in slurry, methane, ammonia and carbon dioxide increase the greenhouse effect. Airborne dust particles can be adhered to by pathogens. E.coli, salmonella, mycoplasma and mycobacteria are common. Viruses such as Aujeszky's disease, Marek's disease and foot-and-mouth disease can be detected in dust particles. On the colonies, the air contains the most mycobacteria in winter and the least in spring. When carbon dioxide concentrations increase with relative humidity around 90%, conditions are favourable for haemolytic staphylococci and streptococci. These types of pathogens can be transported up to 30 km from the site (*Szabó* 1999). Slurry can destroy natural vegetation by killing certain plant species. If slurry is not properly managed on the farm, it can attract large numbers of disease-carrying flies and mosquitoes (*Szabó* 1999). Therefore, proper management of slurry is essential to avoid environmental impacts and increase nutrient recycling (*Brockmann et al.* 2014).

Environmental aspects of organostannic fertilisation. Only properly treated, well-matured manure should be used for fertilisation. The degradation of manure in the soil takes 3–4 years, so it is recommended to apply manure every 4–5 years at a rate of 30–50 t/ha (*Szabó* 1999).

In the Netherlands, measures have been taken to reduce the environmental impact of manure spreading in livestock areas, e.g. the number of animals allowed on farms is linked to the amount of land available. As part of the tasks of integrated management, the quality of manure must be defined in a standard and part of the manure must be exported in the form of dry pellets. In England, N nutrient management in vulnerable catchments is regulated. The regulations state that organic fertilisers and fertilisers should only be used in economically efficient quantities. Organic fertilisers are limited to 175 kg/ha/year. Poultry manure and slurry should no longer be used in these areas in late summer and autumn (*Németh* 2001). In England, the Code of Good Agricultural Practice sets out the conditions for organic manure application. It lists the areas where organ manure should not be used. It specifies the conditions for storage of organic fertilisers, the time and method of application and sets a maximum application rate of 250 kg N/ha/year (*MAFF* 1991, *Németh* 2001). It is in the interest of the farm that the slurry is used on the farm. It is not a question of protecting slurry against its harmful effects on the environment, but of preventing it from becoming a pollutant by using it rationally (*Vermes* 1978). A plan should be drawn up for the use of slurry in nutrient management. This requires a genetic soil map, an annual nutrient analysis, a nutrient cartogram, a nutrient balance, a slurry application schedule and a fertilisation plan. The planning of the amount of slurry to be used in nutrient replenishment and the choice of application technology should also take into account the site conditions (*Csaba* 1978).

8.2. Fertilisation and the environment

The use of fertilisers is key to increasing productivity, but inappropriate nutrient addition (overuse) results in environmental damage and soil degradation (*Szabó* 1999, *Tóth* 2003). The detrimental effect is manifested in soil acidification, nitrate enrichment of groundwater and eutrophication of natural waters (*Szabó* 1999, *Franzluebbers* 2007, *Herrero 2010*). Continued and inappropriate use of fertilisers leads to toxicity and deficiencies of some major and minor nutrients (*Verma et al.* 2020), as well as economic losses and health risks (*Jenkinson* 2001).

Impact of fertilisers on soil. Fertilisers can affect soil chemistry. This means that fertilisers can be physiologically acidic, neutral or alkaline. The active substance is present in the form of a cation or an anion. When the plant uses the nutrients, the accompanying ion is retained in the soil, which if anion, is attached to a hydrogen ion and the soil becomes acidic, if cationic, a hydroxyl group is added and the soil becomes alkaline. If both the anion and cation in the fertiliser fix nutrients, the effect is balanced. The soils also have an attenuation capacity. In soils with a low attenuation capacity, changes in soil chemistry can be more pronounced and occur more rapidly than in soils with a higher attenuation capacity (*Nagy* 2012).

Fertilisers include some that shift the pH of the soil towards acidity, but also some that are alkalising or neutral. They can directly affect the pH of the soil solution during dissolution (direct or chemical acidity), but in some cases the different forms of so-called indirect acidity are more important: physiological acidity, transformational acidity, adsorption acidity and leaching acidity (*Tóth* 2003). Excessive use of ammonium sulphate, ammonium chloride, potassium sulphate, potassium chloride over many years results in soil acidification, while calcium nitrate and sodium nitrate result in alkalinisation of soils. Carriers and additives in fertilisers can modify the effects of fertilisers on soils, e.g. calcium salts in pesticides compensate for the acidifying effect (*Stefanovits* 1992). The acidifying effect of fertilisers is mainly pronounced in soils poor in colloids and with low buffer capacity (*Tóth* 2003). The acid load of fertilisers used in Hungary exceeds that of acid rain (*Table 5*).

Table 5. Estimated acid loads in Hungary

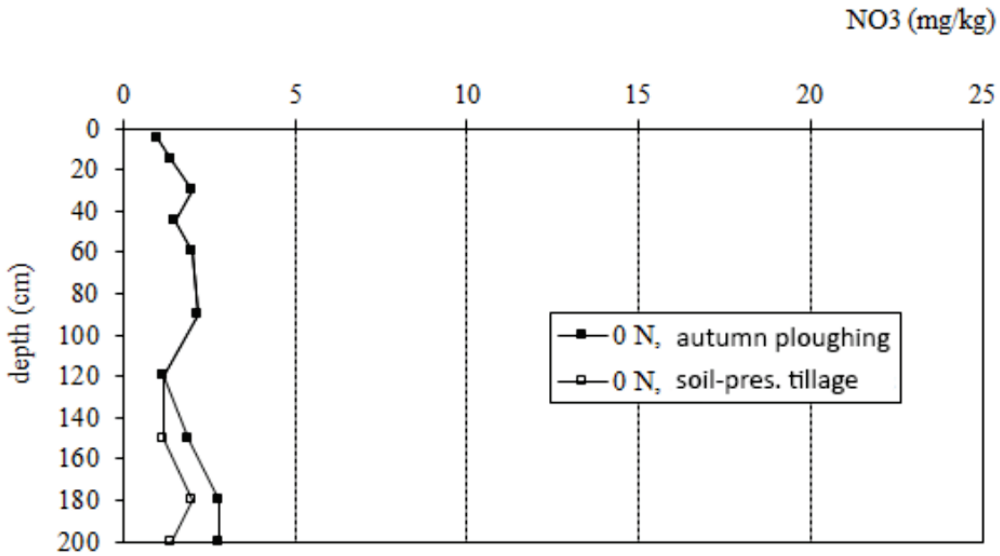
Source of acid load	Acid load dose	Average acid load (kmol/ha/year)
Ammonium nitrate	118 kgN/ha	5,0
Carbamide	118 kgN/ha	5,7
Ammonium sulphate	118 kgN/ha	13,7
Superphosphate	78 kgP/ha	0,5
Acid rain	573 mm	0,18

Source: *Szabó* 1999

If fertilisers are chosen with the soil properties in mind, they can improve the soil rather than worsen it. In acidic soils, therefore, alkalising or neutral fertilisers should be used, while in alkaline soils acidifying fertilisers should be used (*Tóth* 2003).

Spring soil nitrate levels were sampled to a depth of 2 m (*Nagy et al.* 2002) in the low-tillage and autumn tillage versions. In the non-fertilised treatment, there was virtually no difference, with differences within the margin of error. The nitrate content of the 120 kg N/ha treatments was several times higher than that of the non-fertilised treatments, and the nitrate content of the regularly ploughed fields increased dramatically with increasing depth compared to the conservation tillage, increasing dramatically below a depth of 2 m (*Figure 32*).

The nitrate content measured at physiological maize maturity in the unfertilised maize with low soil stress is almost constant up to a depth of 2 m, running along a vertical line (*Figure 33*). In the unfertilised autumn field, however, the nitrate content increases gradually below a depth of 150 cm. In the fertilised treatments, the nitrate profile measured in the two tillage treatments is similar. It can be clearly seen that maize mostly took up and utilised nitrate in the layer between 0–160 cm. The soil nitrate content was higher in all layers in the autumn ploughing. The difference increases below the 180 cm layer and further increases below the 2 m layer (*Nagy et al.* 2002).


Nitrate content of non-fertilised treatments (mg/kg) 5th April 2000

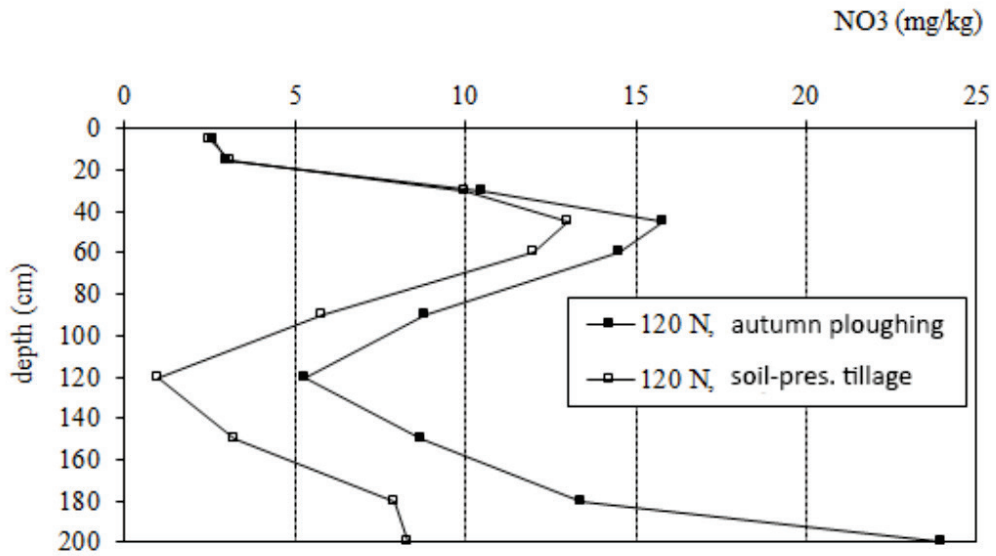

Nitrate content of fertilised treatments (mg/kg) 5th April 2000.

Figure 32. Initial soil nitrate content at the beginning of the growing season (Source: *Nagy et al.* 2002)

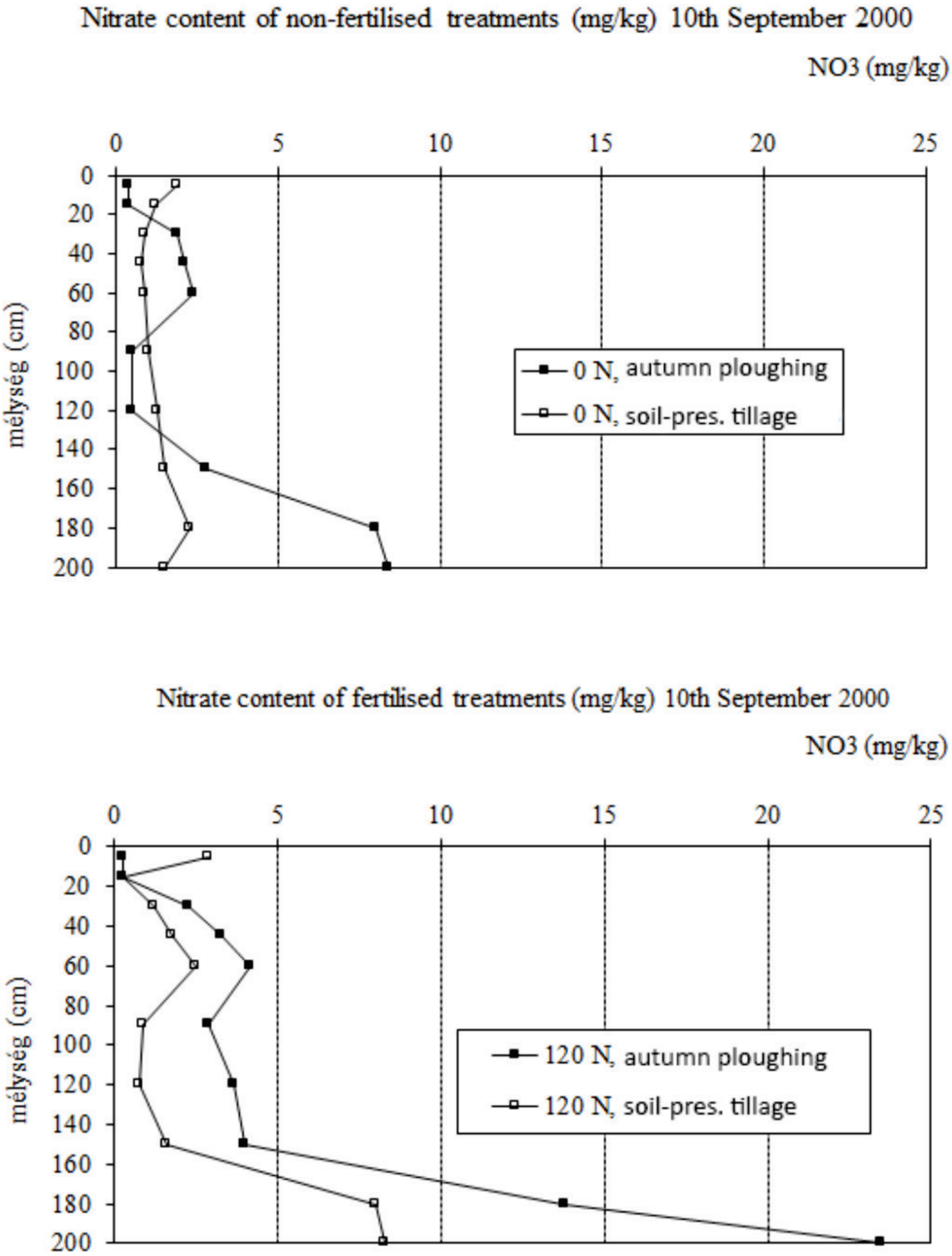


Figure 33. Soil nitrate content at the end of the growing season
(Source: *Nagy et al.* 2002)

Ványiné Széles et al. (2012a) investigated the effect of N fertilisation and irrigation on soil nitrate-N content in dry and wet years. They found that in dry years, nitrate-N concentrations in naturally nutrient-rich plots were 0.6–2.7 mg kg^{-1}. Nitrate-N in the soil accumulated in a 40 cm section near the surface as a result of N fertilisation prior to seeding. The maximum accumulation was in the upper 5 cm layer, with soil nitrate-N concentrations decreasing sharply towards the deeper layers. The amount of nitrate-N measured at the accumulation level was 11.7–23.0 mg kg kg^{-1} at moderate fertiliser doses (30–60 kg/ha N) and 33.9–56.6 mg kg kg^{-1} at moderate and high fertiliser doses (90–150 kg/ha N) (*Figure 34*). Below the accumulation zone, in the 0.4–1.2 m section of the soil, the nitrate-N content of the soil was extremely low (1–7 mg kg^{-1}) at all N doses during all three test dates.) In rainy crop years, lower nitrate-N concentrations (0.3–2.9 mg kg^{-1}) were found in unfertilised plots. The accumulation zone of fertiliser applied in spring peaked in the 0.4–0.6 m layer at all three test dates, which can be explained by the higher than average precipitation in autumn and early spring. During the accumulation zone, soil mineral N concentrations did not exceed 8 mg kg^{-1}.

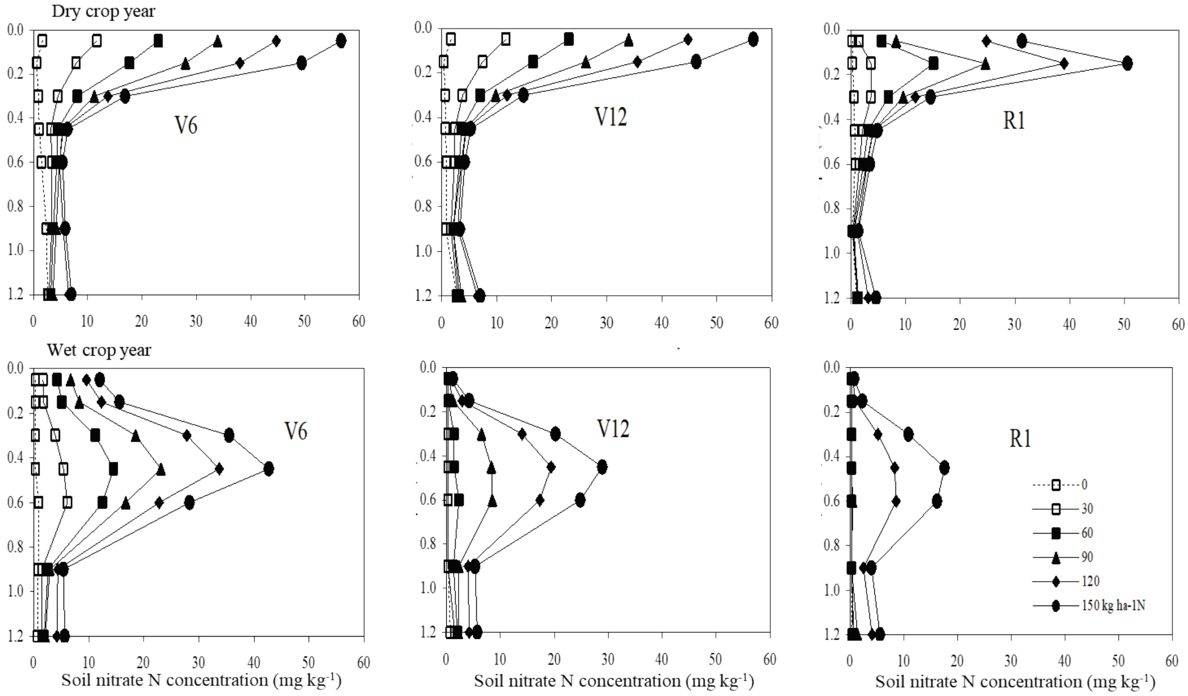


Figure 34. Effect of fertiliser application on soil nitrate-N content in 1.2 m soil profile in maize at three growth stages
(Source: *Ványiné Széles et al.* 2012a)

Yan et al. (2016) investigated nitrate accumulation in Northeast China in a 6-year field maize experiment. Four treatments were applied: No N fertilisation (CK); conventional fertilisation with high N (FC) (applied by more than 40% of farmers); recommended fertilisation (RF) with low N, N amount calculated based on soil test and yield target; controlled release fertilisers (CRF). The RF and CRF treatments reduced nitrate nitrogen in the 0–90 cm soil layer by 16.6 and 39.5% on average, respectively, and achieved relatively high yields compared to the FC treatment. High rainfall in all fertiliser treatments resulted in nitrate nitrogen leaching in the deeper soil layer. During the six years of the experiment, the maximum nitrate nitrogen in the 0–90 cm soil layer was 81.4 kg N/ha at a fertiliser rate of 250 kg N/ha (*Figure 35*). Therefore, the best fertilisation strategy to reduce nitrate accumulation should take into account both soil properties and precipitation.

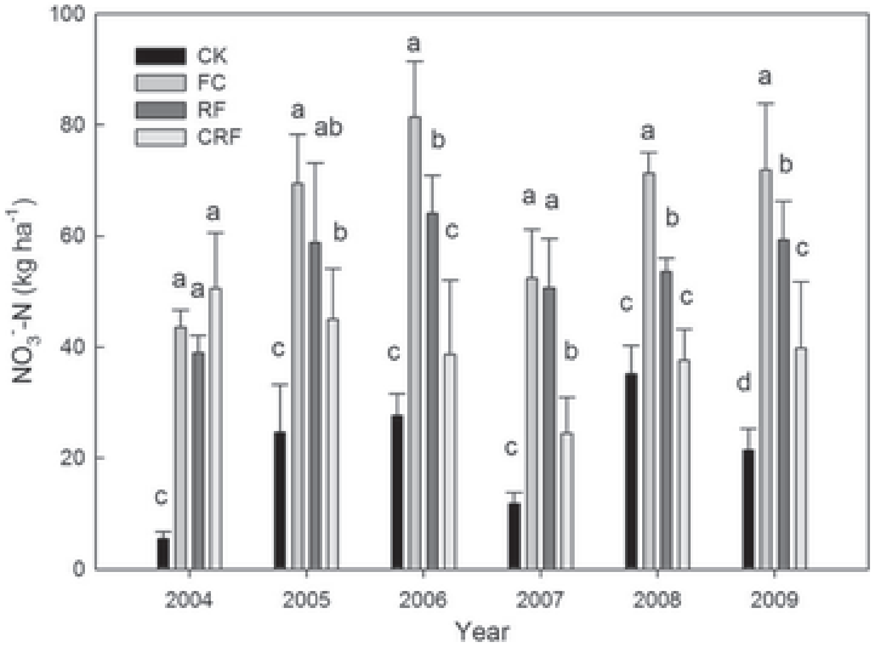


Figure 1.35. Evolution of nitrate content in the 0–90 cm soil layer
(Source: *Yan et al.* 2016)

Acidification of the soil is caused by leaching, which can be caused by acid rain and fertilisers. When acidic compounds are added to the soil, the basic compounds disappear and the processes that produce acid or protons take over. The extent of leaching depends on the vegetation, for example, grassland vegetation has less leaching than forest soils. In hilly areas, leaching may be less due to surface run-off, while on the other hand, carbonate bedrock (e.g. limestone, dolomite, marl, basalt, gabbro) exposed to the surface by erosion may inhibit acidification (*Kovács* 1999).

Fertilisation can also change the rate of oxidation and reduction processes in the soil. The ammonium ion is easily oxidised and therefore aids reduction processes, while the nitrate and sulphate ions are easily reduced and therefore accelerate oxidation processes. The oxidation of sulphate ions produces hydrogen sulphide and sulphite compounds. The reduction of sulphates, on the other hand, occurs only under highly anaerobic conditions, for example in inland waters (*Stefanovits* 1992).

Fertilisers also contain contaminants that can enter the soil and then enter the human body through plants and the meat of house pets. Using IPC techniques, 26 elements have been investigated, of which only selenium was not found in fertilisers (*Kádár* 1991, *Szabó* 1999). Pesticides can contain calcium, phosphorus and strontium. Phosphorus fertilisers contain calcium, magnesium and sulphur in % and Al, Fe, K, Na, Si, Sr in tenths of %. Superphosphate may also contain Sr and As. Coleophosphates and North African hyperphosphate contain Ca, Mn, Sr, Cd, Cr, Ni, Zn. North African hyperphosphate contains higher amounts of trace elements Cd, Cr, Ni and Zn. Potassium fertilisers contain less trace elements such as Cu, Cd, Ba, Sr, Zn, Mn. As, Co, Cr, Hg, Pb, Mo were not detected (*Nagy* 2012).

Impact of fertilisers on groundwater and natural waters. Nitrates can leach with precipitation, as nitrate-N does not form salts that are not easily soluble in the soil and does not adsorb on colloids (*Szabó* 1999). In temperate regions, nitrate leaching can occur mainly in the autumn-winter period (*Németh* 2001). Phosphorus leaching from the soil is not significant because phosphorus fixation processes occur rapidly in the soil, i.e. phosphorus losses are usually not more than 0.1–0.2 kg/ha. Potassium leaching is also only significant in colloid-poor, low plasticity soils. Potassium loss is about 5% on low plasticity soils and 2% on high plasticity soils.

The high nitrate content of groundwater is a problem in 15–20% of villages, as it can enter the human body through drinking water. In infants it can cause methemoglobinemia, and in older people it can promote cancer (*Várnagy* and *Budai* 1995). The water quality standard is 20 mg/l, while 40 mg/l is acceptable (*Szabó* 1999). According to the European Community Drinking Water Quality Directive, levels above 50 mg/l are not of drinking water quality. The Directive also contains a recommendation setting the permissible nitrate concentration at 25 mg/l (*Németh* 2001). Nitrate moves with water, so the amount discharged depends on the amount of water and its nitrate concentration. The nitrate concentration in groundwater varies, sometimes between 50 and 200 mg/l, and in other cases nitrate levels in groundwater can reach up to 1000 mg/l (*Szabó* 1999). Fertilisation can increase the salinity of the soil solution, resulting in an increase in osmotic pressure and a change in the ionic composition of the soil solution. Soil colloidal changes also occur due to an increase in the salt concentration in the soil solution (*Stefanovits* 1992).

In the subsoil, denitrification can result in the accumulation of sulphates, iron compounds and bicarbonates in the groundwater. Carriers from fertilisers may also be present as contaminants. Sulphur from superphosphate and sodium and chlorine from potassium salt can be released to groundwater.

During erosion, phosphorus and potassium can enter living waters with the topsoil carried away by water. Phosphorus is a greater contributor to eutrophication than nitrogen because the productivity of aquatic ecosystems depends primarily on phosphorus availability. In the presence of phosphorus abundance, algae first proliferate and then die as a result of overgrowth. As organic matter decomposes, there is a lack of oxygen, which causes fish to die. In an oxygen-depleted environment, anaerobic decomposition occurs and methane and hydrogen sulphide are produced (*Kádár* 1992). Potassium does not promote eutrophication because it does not limit the growth of aquatic organisms (*Szabó* 1999).

Burnt lime can be carried into lakes by groundwater movement and cause alkalinisation of the water. When the pH reaches 9, the respiratory gills of the fish are damaged. Fertilisers containing phosphorus and ammonium nitrate can cause fungal growth and ammonia poisoning (*Várnagy* and *Budai* 1995).

The impact of fertilisers on the air. Gaseous nitrogen loss can be as high as 10–35% of the nitrogen content of the fertiliser, depending on the form of the nitrogen fertiliser, pH and redox conditions.

Ammonia salts are released from alkaline soils to ammonia, which is released to the air through the soil surface (*Szabó* 1999). The annual growth rate of nitrous oxide in the atmosphere is 0.4%, due to increasing N fertilisation, application of concentrated slurry to cropland and, to a lesser extent, the burning of fossil fuels (*Sántha* 1996).

Other consequences. Nitrate accumulation occurs without yield reduction and without damage to the crop. Nitrate accumulation occurs when the plant is unable to incorporate the uptaken nitrate into proteins due to lack of light, water or other nutrients

(*Szabó* 1999). Most nitrate accumulates in the juvenile shoot and leaves. Lower concentrations in vegetables, fruits and seeds are also dangerous (*Kádár* 1992). Certain bacteria can convert nitrate to nitrite, which oxidises the iron ion of haemoglobin to form methemoglobin, which cannot release oxygen. Methemoglobinemia is particularly dangerous for infants (*Várnagy* and *Budai* 1995).

Superphosphate contains fluoride, which can contaminate our drinking water sources if it is released into groundwater. High levels of fluorine can cause fluorosis in humans and animals. Potassium fertilisers can release large amounts of potassium into the animal body, resulting in hyperkalemia (*Várnagy* and *Budai* 1995). Excessive nitrogen fertilisation results in the release of nitrogen monoxide and nitrogen dioxide into the air, where they are chemically reacted to nitric acid, and thus play a role in acid rain (*Sántha* 1996).

8.3 Fertilisation and environmental protection, technical advice

Some argue that environmental pressures can be reduced by using organic matter management technology, rather than fertiliser. This is not feasible because there is not enough organic manure of sufficient quantity and quality available in Hungary. Rational fertilisation is not necessarily environmentally harmful, because only the amount of fertiliser that is necessary for the uninterrupted development of the crop under the given conditions is applied, minimising fertiliser losses (*Kádár* 1992, *Németh* 1995, Nagy 2007).

From an environmental point of view, it is more important to adapt nutrient supply to crop needs, nutrient uptake dynamics and site conditions (*Láng* and *Csete* 1992, *Várallyay* and *Németh* 1996, *Németh* 2001, *Nagy* 2012). Sustainable agricultural development requires a shift from mechanical to dynamic fertilisation practices. The basic elements of this are: optimal use of available nutrient sources, consideration of nutrient cycling, greater consideration of the duration effect of fertilisation, avoidance of unwanted side effects of fertilisation (*Várallyay* and *Németh* 1996, *Németh* 1996).

Preventing erosion is an important task, not only to prevent water pollution, but also to maintain nutrient-rich soil levels where they are needed (*Németh* 2001).

In order to achieve a more adaptable nutrient management, it is essential to solve the technical and technological conditions of fertiliser application necessary for the individual management of sub-areas with different characteristics within the field. The use of electronics and automation systems that allow controlled application is necessary. The use of technical solutions based on satellite positioning is in line with environmental requirements (*Láng* and *Csete* 1992, *Ruzsányi* and *Pepó* 1999, *Nyéki et al.* 2020).

Knowledge of the area is important when giving fertilisation advice. The different soil properties can be mapped using GIS and GPS systems. The different sub-areas within the table can be located using GPS systems and subsequently identified, so that after testing soil samples from different parts of the field, the results can be used to determine the nutrient supply and the amount of fertiliser required. Based on the maps, a GPS system can be used for the individual management of fields with different characteristics (*Németh* 2001).

Plant analysis helps rational nutrient management and increases the reliability of expert advice. Plant analyses can be used to determine the nutritional status of plants, and thus the effect and utilisation of fertiliser can be determined and monitored on a spatial basis (*Kádár* 1998).

Nutrient replenishment should be based on fertilisation advice. When preparing the advisory, soil properties, soil test results, specific nutrient content of the crop, the history of the field, the predictable yield level and the nutrient requirements of the crop should be taken into account (*Figure 36*) (*Németh* 1995, *Nagy* 2007).

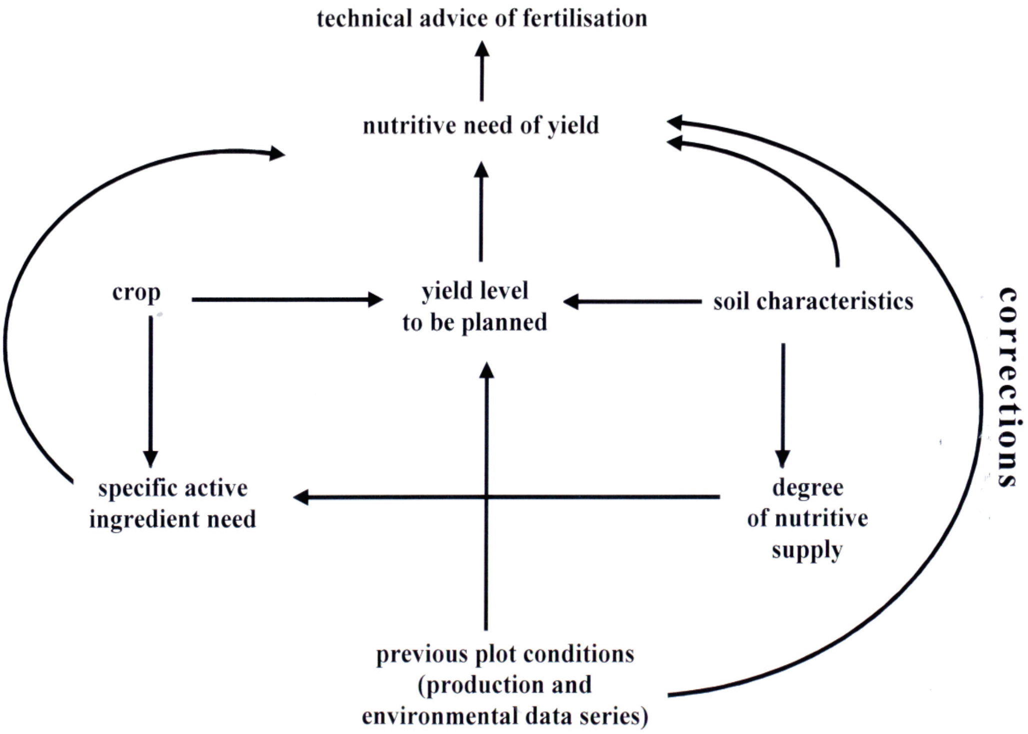


Figure 36. Fertilisation advisory council

(Source: *Németh* 1995)

The nutrient requirements of the crop can be determined in long-term and other fertilisation experiments, and information on the history of the field can be obtained from soil tests and simplified nutrient balance calculations (*Németh* 1995).

In our country, there is no complex model of decision support for crop production on the market. We have decision support systems that are suitable for nutrient replenishment planning and for field registry (e.g. Farmer software, TAKI–MGKI, Kemira, Talajerő Kht. etc.). The shortcoming of the existing advisory systems is that they are not able to measure the economic efficiency of the nutrients to be applied and thus their marginal efficiency. They are not able to determine the yield increase per unit of input (income analysis). However, the Institute of Land Use, Engineering and Regional Development of the University of Debrecen (MÉK) has developed the 4M-ECO nutrient replenishment system in collaboration with the MTA ATK TAKI, taking into account decades of experimental experience. *The structure of the decision support system is as follows: level 1: Descriptive (input database) part, level 2: Ecological module, level 3: Agro-economic module, level 4: Optimisation module.*

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Figures

a) b)

Photo 1.1. Maize with nitrogen deficiency.
Source: *nue.okstate.edu/Spatial_N_variability.htm*

Photo 1.2. Phosphorus deficient maize plant.
Source: *Kalocsai R.* 2004

Photo 1.3. Potassium-deficient plant.
Source: *stockxpert.hu*

Photo 1.4. Calcium-deficient maize
Source : *https://www.magro.hu/agrarhirek/a-kukorica-hianytuneteinek-kezeleserol-nem-csak-profi-termeloknek-promo/*

Photo 1.5a. Maize with magnesium deficiency
Source : *https://www.magro.hu/agrarhirek/*

Photo 1.5b. Maize with magnesium deficiency
Source : *https://agraragazat.hu/hir/a-kukorica-margojara/*

Photo 1.6. Sulphur deficiency symptom on maize plant
Source *: https://static.agriculture.com/styles/*

Photo 1.7. Zinc deficiency on young leaves „Bud whitening"
Source *: https://www.pioneer.com/us/agronomy/zinc_deficiencies*

Photo 1.8. Severe zinc deficiency in the V12 maize plant
Source : https://www.pioneer.com/us/agronomy/zinc_deficiencies

Photo 1.9. Iron-deficient maize plant
Source : *https://landresources.montana.edu/soilfertility/irondeficiency.html*

Photo 1.10. Maize plant with manganese deficiency
Source : *Sharma, M. K., Kumar, P.* 2019, *https://hu.pinterest.com/pin/526006431447749410/*

Photo 1.11. Boron deficiency (a) Severe boron deficiency (b)
Source : *https://brandt.co/our-insights/wet-weather-leads-to-increased-boron-deficiencies/*

Photo 1.12. Molybdenum deficiency
Source : *https://www.thedailygarden.us/garden-word-of-the-day/molybdenum*

Photo 1.13. Copper shortage
Source : *http://agrigoaexpert.res.in/icar/category/agriculture/fieldcrops/cereals/Deficiency*

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