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

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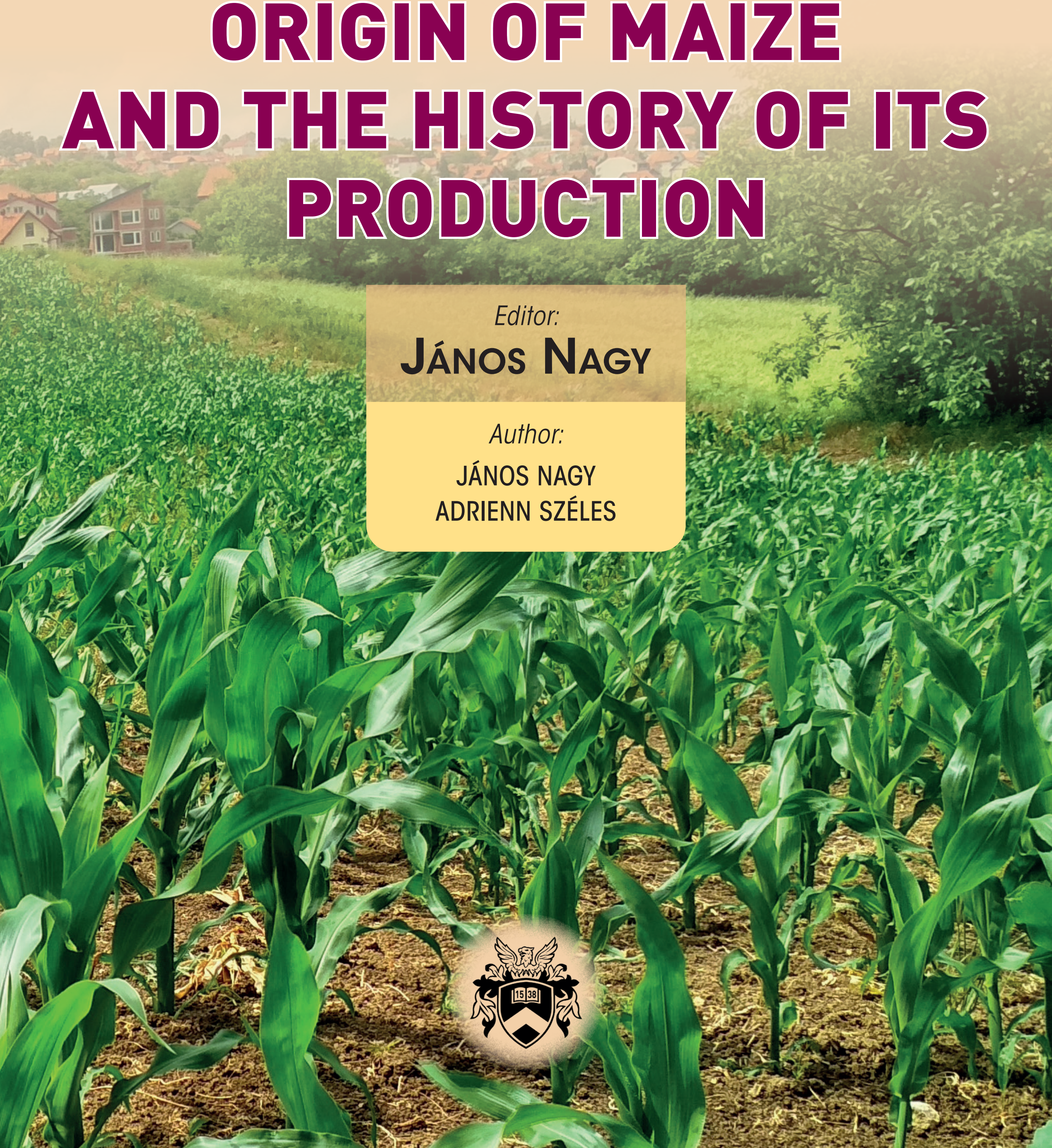

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Academic lecture notes

Debreceni Egyetemi Kiadó
Debrecen University Press
2022

Reviewer:
Prof. Dr. Jolánkai Márton (MATE)

Cover photos:
*pexels.com*

ISBN 978-963-615-073-0 (pdf)

Kiadta: a Debreceni Egyetemi Kiadó, az 1795-ben alapított
Magyar Könyvkiadók és Könyvterjesztők Egyesülésének a tagja
dupress.unideb.hu
Felelős kiadó: Karácsony Gyöngyi
Borítóterv és nyomdai előkészítés: M. Szabó Monika
A nyomdai munkálatokat a Debreceni Egyetem sokszorosítóüzeme végezte 2022-ben

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# FOREWORD

The international success of maize research at the University of Debrecen is marked by the late Professor János Németh in Nagy's book "Maize production" (2006):

“The honoured reader holds a concise treatment of modern agricultural knowledge in her/his hand with special reference to the cultivation of a single species, one of the leading crops of the world, the staple food for almost the half of contemporary mankind and potentially the most significant agricultural crop of Hungary. Maize is the most important (about ¾) constituent in all animal feeds, moreover, maize silage is an absolutely indispensable forage of ruminants. In addition to that, Hungary developed its seed grain production capacity of many modern hybrids, which are grown for special purposes (grain for human food, processing industry, ethanol fuel, seed grain and silage for animal feed, etc.) in all countries of the moderate and tropical climate. Immediately consumed and processed commodities represent about 10% of the total produced. Chips, grits, flour, oil, starch, sugar, etc. are increasingly demanded in Hungary too. Many, densely populated regions of the world consider maize as the basis of their nutrition. Recently, also environmental wrapping material has been made from maize. As one of the new sources of fuel for engines, bioethanol is praised as being renewable and an alternative of mineral oil. Those tendencies are increasing continuously. A couple of reasons suggest that the present work would find readers not only in the society of growers and professional entrepreneurs including students of rural economy, but also among literate citizens interested in recent topics of survival and environmental conservation. The history of a cultivated plant over a period comprising 6000 years in the New World (as the archaeological findings suggested) is a fascinating lecture comparable with the parallel history of ancient civilisations of the Old World. The author, János Nagy, gathered great many references, which dealt with the beginning from the earliest records and with growing intensity on the development of modern scientific approaches on agricultural technology as well as plant breeding. Henry A. Wallace has been the first genius, who started his revolutionary work in the USA during the twenties of the 20th century with inbreeding and crossing inbred lines of maize and earned incomparable appreciation not only in plant breeding but also in the theory of genetics. In 1955, he wrote: ”Nuclear energy is a popular issue nowadays. Nevertheless, I am convinced that historians will consider the exploitation of hybrid effect to have the same importance”

It is worth while to remember of the first European pioneers of exploiting hybrid vigour in plant breeding during the thirties of the last century are Hungarians: Rudolf Fleischmann and László Berzsenyi-Janosits; subsequently, Endre Pap produced the first double cross maize hybrid, Mv5 in 1953, as the first hybrid recognised in Europe outside the USA. This state registration opened the new epoch of hybrid maize, which still keeps to unfold itself. Mv5 preceded by several years the hybrids released by French and Yugoslavian breeders.

The intense research in universities and activity in seed companies related to maize breeding is boasting worldwide since more than 80 years. Outstanding achievements are to be ascribed to János Surányi (1957), Béla Győrffy (1965) and Zoltán Menyhért (1985). Not only the origin, botany, physiology of maize has been studied but also ecological conditions have been treated in relation of interactions with agrotechnical moments. Students of applying agricultural techniques, as professor János Nagy, are indispensable in successful up to date maize growing. Inferences based on carefully planned reliable long-term field experiments are the strong points of the present book. Interactions of the main components of agronomical interventions (tillage x fertilisation x planting density x irrigation) are profoundly influencing the results, which are unique for Europe, but are also remarkable from the point of view of America, the site of the origin of maize.

This book deals with a plant species, which is near to the top of the list representing most important crops of the world. It is grown on 135 million of hectares and produces 575 million tons of grain. Almost all countries of the world are producing maize, which is continuously improved by breeding, and due to those efforts, the worldwide increment of yields is estimated to be 1 – 1.7 % per year. The mean yield estimated in the 1920es was 1.5 t/ha, which has to be multiplied by 3 to 4 to express the present status. The agronomical conditions have been improved immensely by irrigation and intense cultivation technologies.

Following the appearance of the first hybrid by crossing inbred lines in Hungary (1953), 11 years elapsed until almost the whole national maize growing area has been occupied by hybrids in 1964. (The appearance and general acceptance of hybrids took relatively very short time in Hungary, whereas nearly thirty years were needed in the USA). In the 1970es integrated maize growing systems have been organised in Hungary (1970: CPS-IKR, 1972: BKR and KSZE, 1973: KITE), which offered a framework for the introduction of the most advanced hybrids, machines and technologies. Those achievements were outstanding in a worldwide relation too. By those reasons, in the next 20-year-long period, the increment of mean yields was 119 kg/ha/year.

Hungarian agriculture experiences, recently, the rearrangement of its ownership structure. In spite of its modest size of agricultural area, Hungarian maize production occupied an important position among the European countries, and we hope, it will keep this position. The seed grain industry and the research capacity with the a system of experimental stations of the country has been highly developed and recognised in the temperate zone agriculture, especially on the surrounding regions of the continent.

As for all agricultural activity, maize growing is aiming simply to produce highly useful commodities through reasonably high yields by the possibly lowest inputs and the less environmental risks securing a safe income for the grower. For that purpose, the book of professor János Nagy will offer decisive help. Not only information will be enhanced, mind and soul enriched, but also the chances of a successful management. Therefore, this up to date repository of professional know-how is recommended sincerely with firm conviction for the interested readers”.

*Dr. János Németh †*

# INTRODUCTION

As a consequence of selection performed by man, maize, one of the ancient cultivated plants lost its abilities definitively to survive in the nature without the care of its breeder. Not only its appearance is unique compared with its closest relatives, but also its significance in human nutrition is a product of close interaction over thousands of years between that plant species and its mentor, *Homo sapiens,* that exceptional living species, which has been able to transform the biosphere according to its own advantage. There is a kind of mystic haze around the hypotheses concerning the origin of the species *Zea mais.* No definite consensus could be found in spite of repeated joint efforts attempted by historians, plant breeders, plant taxonomists and archaeologists. Some initial points, however, are clear since long: the plant appeared first in America. During the last century, alternative hypotheses appeared in each about 20-year-long interval either adding some certainty to the picture, or submerged soon into oblivion (*Nagy* 2021). The conceptions emerging one after the other haunted the longer the more blurred they were (*Weatherwax* 1918). More simple conceits gained popularity on the short run (*Mangelsdorf & Reeves 1939*).

The most relevant documents related to the origins of the cultivated maize have been found one century ago in Mexico (*Harshberger* 1900). The lines, *Tb-l* and *Tga-l* were considered to be botanical proofs (with excellent adaptability and clear traits akin with the cultivated maize), but they turned out to be hybrids between the teosinte and maize, in other words, they are not entirely wild lines. The following 20 years expanded our knowledge related to those spontaneous hybrids. *Weatherwax* (1918) forwarded his hypothesis of the common origin of maize and teosinte, whereas *Collins* (1920) dealt with the conditions f hybridisation. Further 20 years elapsed until *Mangelsdorf & Reeves* (1939) published their triple hypothesis, which did not accept teosinte as an original wild species but a hybrid. In 1942, *Edgar Anderson* and *Hugh Cutler* published their joint study, which became decisive in the history of maize research. Further twenty years of investigation aimed to explore the relations between existing primitive maize populations and the wild teosinte and of *Tripsacum,* a related genus. During the 1970s, the hypothesis of teosinte being the ancestor gained attention (*Galinat* 1971, *Beadle* 1972, *Iltis* 1972). Proofs based on the iso-enzyme pattern indicated that teosinte of Balsas may represent the nearest ancestor of maize (*Doebley* 1990). Certainly, catastrophic morphological transmutations ought to be responsible for the actual form of the maize plant (*Iltis* 1983). The abrupt transformation of the teosinte inflorescence ensued to the actual form of the maize ear with eight rows of kernels (*Galinat* 2001). All those hypotheses represent fragments of a complicated picture, which needs further completion, and that endeavour keeps being exciting. Maize cultivation of Hungary developed slowly over the last centuries and the yields were rather low. During 1900–1950, the mean yield hardly trespassed 2 t/ha. In 1982, it could be raised to 8.86 t/ha. The progress of a three-fold increment is due to genetic improvement, the general use of hybrid seed, the use of chemical manure, the developing water husbandry, the modern cultivation technologies and the up to date expertise. At the same time, Hungarian agriculture has been forced to concentrate on the increasing yields and profitability, whereas to neglect many deleterious consequences showing up in environmental conservation and policies of healthy nourishment. One of the major concerns is the wide variation of annual yields. The site of our own research related to maize growing is the Agricultural Centre of the Debrecen University, which is an outstanding workshop of crop science in the European region. Results obtained in multi-factorial and long-term field experiments (crop rotation x tillage x nutrition x watering x plant density x genotype) are reported in the present book *(see Figures 1–3, and a coloured supplement*). The research program is based on the principles of a project initiated by *Győrffy* and *Berzsenyi* at Martonvásár several ten years ago.

In our research, We are committed to an agro-ecological approach, which is not centred on productivity alone, but considered also the *sustainability* of the growing system to be introduced. Sustainable production ought to be characterised by (a) a permanent, i.e. not declining tendency of productivity and of its components, (b) adequate stability and reliability of yields, (c) maintenance of quality in the agro-ecosystem. The conservation of sustainability could be secured on the basis of indications derived from results of *long-term experiments.* A permanent monitoring of the appearance of new genotypes of maize hybrids is necessary as well as their adaptability and interactions with individual components of the technology applied. Optimisation of the components of the interventions and their combinations (tillage x nutrition x watering x plant density x genotype) is performed by means of up to date mathematical methods. Breeding, registration of new hybrid combinations and their extension is based on the information raised by the permanently maintained experiments. For that reason, an ideal growing technology should be adapted to a specific site and to a specific hybrid. It would become beneficial from the point of view of economy, yield security, and will economise chemicals, thus spare the environment.

The first volume of our lecture note series deals with the origin of maize, its history of production, as well as its morphology and development.

*János Nagy – Adrienn Széles*

## 1. ORIGIN OF MAIZE AND THE HISTORY OF ITS PRODUCTION

The more vague was the information on the origin of maize (*Weatherwax,* 1918), the more timeless were the relevant hypotheses. More concrete ideas lasted for a shorter time, though they were more popular (as *Mangelsdorf* & *Reeves* forwarded the triple assumption in 1939). Additional proofs appeared each 20-year-period, whereupon former hypotheses faded away with time.

About 100 years ago, botanical observations in Mexico served as a basis for a hypothesis concerning the origin of maize (*Harshberger* 1900). The wild *Tb-l* and *Tga-l* lines received special attention (with their outstanding adaptability and all characters corresponding with the species of maize) as long as it was not evident that they were hybrids between maize and teosinte instead of being wild taxa. Information related to teosinte or maize x teosinte hybrids increased gradually. *Weatherwax* (1918) published his postulated version of the origins of maize and teosinte, whereas *Collins* & *Kempton* (1920) presented their theories on hybridisation. Nineteen years later, *Mangelsdorf* & *Reeves* (1939) proposed the triple assumption, which considered teosinte to be a hybrid, not an ancient line. The contention of hybrid origin excluded the possibility of wild, natural teosinte populations; meanwhile, the studies of *Longley* (1941a,b) on chromosome numbers were not taken into account. The study of *Anderson* & *Cutler* (1942) represented a watershed in this research as they initiated investigations over twenty years to explore the variation of primitive maize varieties, comparing also wild lines of teosinte and taxonomic units of the genus *Tripsacum*.

Around the mid 1960s, the last leaflet was published dealing with “races of *Zea mays*” and studies of teosinte as “the closest relative of maize” (*Wilkes* 1967), furthermore, the background related to *Tripsacum* was elaborated (*Randolph* 1970, *de Wet* & *Harlan* 1978).

Summit talks organised on the origin of maize in 1969 and 1972 dealt with teosinte as the real ancestor, replacing the former triple assumption (*Galinat* 1971, *Beadle* 1972, *Iltis* 1972). Isozyme studies stated that the teosinte of Balsas is a variant of the closest maize ancestor (*Doebley* 1990). “Catastrophic sexual transmutations” must have occurred in the ancient population as a decisive step to arrive at the common form of the actual maize (*Iltis* 1983), and a quick hybridisation with teosinte facilitated the appearance of eight-row cobs (*Galinat* 2001). Those assumptions contain valuable ideas but there remain enigmatic details to be explored.

## 1.1. The provenance of maize

There is still some lack of clarity surrounding maize and in spite of it being one of the most explored cultivated plants its provenance cannot be established with complete certainty. There is one question which enjoys consensus: America is the home of the specie, and it is the most important food in the New World. Earlier opinion that the Old World was the provenance (*Bonafous* 1836) has lost its credit already and the ambiguity continued around Central or South America only (*Győrffy et al.* 1965). The main difficulty stems from the fact that no wild growing ancestor could be identified without question as with most cultivated plants.

*Geisler* (1980) deemed Southern Brazil, Northeast Brazil and Paraguay to be the centre of origin. Central America and Mexico has been considered as a secondary centre. *Galinat* (1979), on the contrary, believed Mexico and Central America to be the centre, from where maize was carried to Peru, Brazil and Argentina, and later to USA and to Canada (*Figure 1.1*).

*Figure 1.1* – Provenance, distribution and areas of production of maize. (Source: *Zscheischler et al.* 1990)

Maize is represented in the cultures of the Mexican Aztecs, Mayas and Peruvian Incas as an important crop. In the carvings of Maya tribes in Central America, corncobs appear regularly. In the agriculture of Mexican Aztecs watering systems were supplied from mountain creeks or lifted from the valleys with outfits of spoon-wheels, all served for maize production. The Peruvian Incas installed huge systems, which are still admirable constructions. They ate maize kernels prepared by cooking or baking (*Lazányi* 1955).

The ancient cultures of the Old World cultivated many species of plants, but any sign indicating maize is found neither in written chronicles nor depicted in artefacts. Also in China, the first traces of maize production appeared two or three decades after the memorable trip of Columbus. Around Beijing (Peking), maize has been grown since the early 18th century, which excludes the supposition of Chinese origin.

*Bonafous* cited several Spanish authors of the 16th, 17th and early 18th century, who reported as the first European travellers in the New World that they were deeply enchanted by the tall stemmed, smooth, long-leaved plants, which as a cereal bore large, golden kernels. People celebrated its harvest with religious devotion (*Surányi* & *Mándy* 1955). At Cuzco, the capital of the Incas, the daughters of the Sun prepared sacrificial maize bread soaked with the blood of immolated beings. In Mexico, idols were formed of maize meal and distributed among jubilant crowds. One of their goddesses, Cinteut, an equivalent of Ceres of ancient Rome, accepted as a sacrifice the offerings of the first harvested crop of maize (her name refers to maize). During the reign of Montezuma, inundations caused famine; therefore, people sold themselves as slaves for food; for a man 500, for a woman 400 corncobs was offered. A thief, who was guilty of having stolen seven cobs of maize, was condemned to death in Mexico. The first Europeans saw maize in Cuba in early November 1492 when two Spaniards attempted to explore the inner part of the island (*Győrffy et al.* 1965). Christopher Columbus fetched the first kernels to Europe on his first trip in 1493. At that date, maize was grown across the American continent from the Canadian Gaspé to the south of Chile, mainly on deforested areas. After felling and burning the trees, the clearing was fallowed for some years before maize was planted.

After the discovery of America, the Spaniards introduced first the smooth and hard kernel varieties of maize (*Lazányi* 1955). The people, aborigines of the West Indies, called the crop ”Mahiz”, which was transformed in Spanish to ”Maíz” and served the as species name of the Linnean terminology, mays, whereas the genus was termed Zea referring to the Greek word ”Zooin” = to live.

In Europe, maize was first considered an ornamental plant, its use in agriculture started in the 17th century. Meanwhile, the Mediterranean trade carried maize together with several other crops of the New World to the Middle East. Rauwolff already observed maize fields in 1574, around the Euphrates River, and took a sample for the herbarium of Leyden. Central

Europe introduced maize from the south east; therefore, the traditional name in Hungary was „törökbúza” (Turkish wheat). The Slavic population of the Balkans adopted maize cultivation in the early 18th century and subsequently, the denomination of „kukorica” appeared in the Hungarian language (*Lazányi* 1955).

## 1.2. The ancient maize cultivation

Maize was an esteemed object of ancient Indian mythology. Some tribes assigned individual deities to the different developmental stages of the maize plant. Sowing was a religious ceremony, as was the fertilisation and the harvesting procedure. It is surmised that also the (genetic) improvement of the crop benefited from that cult. The goddess of maize received in her temple the most beautiful cobs, and their kernels were sown in the next season. *Weatherwax* (1954*)* summarised the reports of many late and recent authors concerning the ancient maize production.

The American aborigines did not practise any technique of soil tillage according to our understanding. The soil was prepared with the felling, burning and extirpating trees and shrubs, followed by levelling of the soil. As fertilizer, tribes living close to rivers placed a fish into each hill of maize.

The terms of sowing was fixed according to astronomical patterns of the sun and the phases of the moon, as well as the budding of trees. The hills (nests) of maize were arranged into rows 45–350 cm apart, whereas within the row the space was about one step. For sowing, 5–6 Indians stood close to each other (one or two steps apart), each carrying a one man-long pointed stick with a stirrup, and made a hole for 4–5 maize kernels, which were covered by foot. The hole makers and sowing girls cooperated in the work (*Figure 1.2*).

The cultivation of maize was limited to the control of weeds, which was performed by a hoe or by hand (*Figure 1.3*). On the altiplano and windy habitats with sufficient precipitation, the hills of growing plants (around 60 cm tall) were moulded up, especially in the Central American region (*Figure 1.4*).

One part of the crop was harvested at the milky or waxy stage for immediate consumption after being baked or grilled. Unripe cobs were frequently stored in burned pits covered with a layer of soil. Cobs were also left on the plant within the protecting husks and picked later for immediate consumption (*Győrffy et al.* 1965).

*Figure 1.2* – Ancient maize sowing in Peru. (Source: *Weatherwax* 1954)

*Figure 1.3* – Ancient maize cultivation in Peru. (Source: *Weatherwax* 1954)

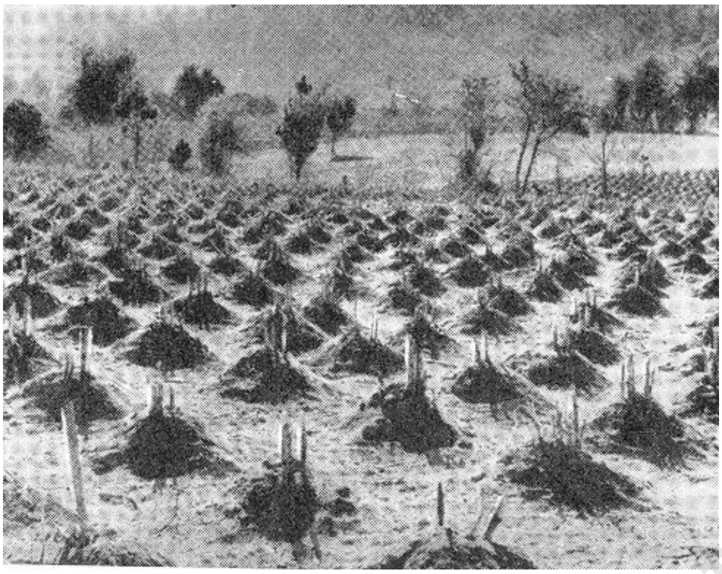

*Figure 1.4* – Moulded up hills of a maize plantation according to the ancient practice in Guatemala.
(Source: *Weatherwax* 1954)

# 2. MORPHOLOGY AND ONTOGENESIS OF MAIZE

## 2.1. Taxonomy and classification of varieties

Maize belongs to the botanical family of grasses as do other cultivated cereals such as wheat and rice. As an exception in this family, maize develops unisexual flowers grouped into separate inflorescence, males in tassels at the terminal position of the main shoot and females in ears on side branches. The first botanical description of the plant (*Lyte* 1578) erroneously recognised the tassel as the sole inflorescence. The only grass species with separate inflorescences is the teosinte, the closest relative of maize. Different varieties and types of teosinte exist in Mexico and on the western slopes of Guatemala, which is proof that this is the centre of origin of maize. Teosinte (*Euchlaena mexicana* Schrad.) and maize are members of the genus *Zea* ($2n = 20, 40$; $x = 10$). The closest relative is the genus *Tripsacum*, which harbours about 20 species ($2n = 36, 54, 72$; $x = 9$) on the American continent; moreover, their centre is also Mexico. The flowers of *Tripsacum* are also unisexual but they grow on the same inflorescences in the terminal position. Male flowers are grouped on the upper part of the panicle, the female flowers at its base (*Dewald et al.* 1987, *Cámara-Hernandez* 1992).

Maize and *Tripsacum* have been crossed successfully, which means that gene exchange between the two species is possible, and the $F_1$ hybrid is fertile. Hybrids between maize and teosinte are easily mad, and the pairing of chromosomes of the species is good or excellent

(*Ting* 1969, *Hsu* 1988). The hybrid generations are successively fertile, except the *Luxuriantes* group. On the contrary, *Tripsacum* x teosinte crosses are problematic; most of the researchers did not succeed, however, a triple interspecific hybrid (maize, teosinte, *Tripsacum*) was produced in 1932 (*Tantravahi* 1968). It is obvious that *Tripsacum* and *Zea* are relatives but teosinte is much more closely related to maize than *Tripsacum*. Interspecific hybrids between *Tripsacum* and teosinte are considered to be also a possible point in the evolution of maize (*Eubanks* 2001a,b,c).

### *2.1.1. The position of maize in taxonomy and its relatives*

During the last 300 years, maize changed its position several times. According to *Surányi* & *Mándy* (1955) the main classifications are: *Linné* (1754) placed it in the XXI. *Monoecia* class as a species of the genus number 926. In the system of *Tuzson* (1926), the *Angiospermae, Monocotyledoneae* class, III. *Glumiferae* branch, 7. *Glumiflorae*) series, *Gramineae* family, *Maydeae* swarm, *Zea* genus. In *Wettstein's* (1935) system IX. *Cormophyta*, II. *Anthophyta* group, 2. *Angiospermae* subgroup, 2. *Monocotyledones* class, 5. *Glumiflorae* series with the sole family *Gramineae,* tribe *Maydeae,* genus *Zea*. According to *Soó* (1953), the species is in his "evolutionary" taxonomy XIV. phylum: *Angiospermatophyta*, II. class: *Monocotyledones,* 5. branch (series E): *Helobiae-Graminales*, XLVIII. series: *Graminales* (*Glumifloreae*), family *Gramineae*, tribe *Maydeae*, genus *Zea.*

The closest relative of maize, *Zea mays* L. of the family *Gramineae* and of the swarm *Maydeae,* the only species being grown as a rare ornamental in Hungary, *Coix* (*Coix lacryma-jobi* L.– "Job's tears") is known. The swarm *Maydeae* is represented in America by two genera with one species of each: *Tripsacum dactyloides* L. (gama-grass) and *Euchlaena mexicana* Schrad. (teosinte) (*Figure 2.1*).

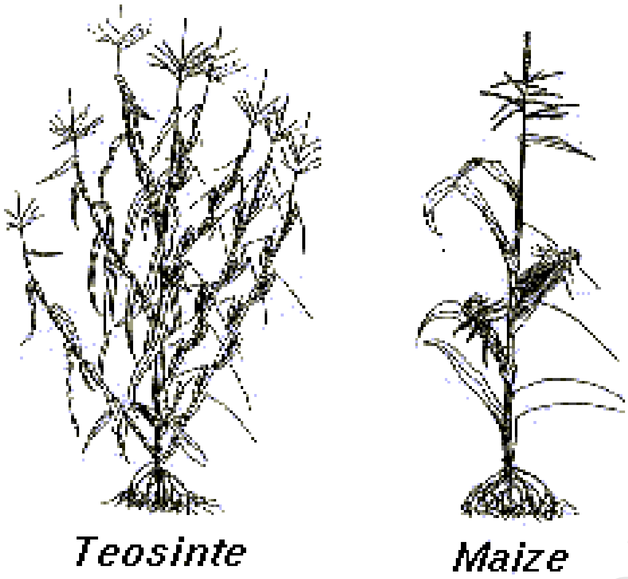

*Figure 2.1* –Teosinte (*Euchlaena mexicana*) and maize. (Source: *Kempton* 1937)

The genus maize is mono-specific, the only species is *Z. mays*. The variability of the species is however large (*Figure 2.2*, *coloured pictures*). The extreme representatives of the species are 50 and 700 cm high, the number of leaves is 8–44, the number of ears per plant is 1–12, the length of ears is 2.5–50 cm, the thousand kernel weight is 50–1200 g and the length of the growing season is 50–160 days.

### *2.1.2. The grouping of maize varieties*

The maize varieties grown today originated with high probability from popcorn and glumaceous types. In the Bat-cave (New-Mexico), there are found remnants of 4000-year-old maize plants, which seemed to be of a perfect maize-type and were the ancestors of the maize grown today. No remnants of a more primitive form have yet been found. Popcorn and glumaceous types are derived from the same ancestor. Different types probably interbred with each other and new recombinations appeared. Teosinte is also thought to have contributed to the variability of today.

Also in Hungary, there are different subspecies or convarieties (*Grebenshchikov* 1954).

*Dent corn* (Zea mays L. convar. dentiformis). At present this convariety is the most important all over the world including Hungary (*Figure 2.3, coloured pictures*). The most productive maize varieties represent this type. The kernels are long, tapering and on the upper end a depression is typical (like on the tooth of the horse). Also the most widely grown hybrids are dent types, as were the varieties earlier bred in Hungary e.g. „F" mezőhegyesi,

„F” korai sárga, Mindszentpusztai sárga, Aranyözön, Szegedi sárga, Bánkúti korai, Magyar fehér lófogú. New Hungarian hybrids include Szegedi SC 352, Hunor and Debreceni SC 377.

*Flour type maize* (Zea mays L. convar. vulgaris) (*Figure 2.4, coloured pictures*). In Hungary, this type was most popular and used as human food. The surface of the kernels is smooth, more or less bright and glass-like. The kernels are broad and large. The plants are smaller and of shorter growing season than the dent type. *Körnicke* (1873) distinguished within this convariety the hard and the soft kernel group. The former contain more protein, whereas the soft ones develop larger kernels. The hard hybrids are more suitable for groats (e.g. Benicia) with white cobs. For silage, the following varieties and hybrids are recommended: Alberta, Szegedi DC 488, Maxima, Szentesi MTC 508 and Szarvasi édesszárú TC.

*Sweet corn* (Zea mays L. convar. saccharata) (*Figure 2.5, coloured pictures*). The economic importance of this group is increasing steadily. The ears are consumed at an earlier stage of maturity (waxy or milky) or processed by the canning or deep freezing industry. The mature kernels are easily recognised by their shrivelled form. As a rule they are smaller and earlier maturing than the average. The endosperm is much sweeter and tasty. New varieties are: Boston, Dallas, Spirit, Jumbo, Challenger, Kecskeméti sárga SC 300, Kecskeméti sárga SC 430 and Rival.

*Pop corn* (Zea mays L. convar. microsperma) (*Figure 2.6, coloured pictures*). In Hungary they are of much more minor importance than in the USA. The kernels are puffed by heating and consumed or processed as confectionary. The kernels are small, very hard and horny. This hard layer encloses the inner, mealy part. The popping quality depends on the relationship between those layers and the water content. In Hungary, the *mouse tooth* and the *rice* types existed. Recently, mainly the *pearl* types are cultivated. Varieties include Jantar F1, Kecskeméti Gyöngy F1. New varieties: Kecskemét aranya, Krémgolyó, Panna, Pehely, K.SC bőtermő and K.SC gyöngy.

The rest of the convarieties, *floury* (Zea mays L. convar. amylacea), *waxy (*Zea mays L. convar. ceratina) (*Figure 2.7, coloured pictures*), *transitory maize (*Zea mays L. convar. aorista), *ambiguous maize* (Zea mays L. convar. amylosaccharata) (*Figure 2.8, coloured pictures*), *ornamental maize* (Zea mays L. convar. japonica) (*Figure 2.9, coloured pictures*), *glumous maize* (Zea mays L. convar. tunicata) (*Figure 2.10, coloured pictures*), are of minor importance.

## 2.2. The morphology of maize

Maize is an annual, monecious herb. It is composed of two parts: the subterranean root system and the aerial shoot system.

### *2.2.1. Root system*

Maize develops – like other grasses – a fibrous root system. (*Figure 2.11*). There are two kinds of roots: 1. primary roots and 2. adventitious or shoot borne roots. The primary roots originate from the radicula of the germ (embryo). At germination, the radicle breaks through the coleorhiza and grows quickly downwards in the soil. Initially the radicle develops much more strongly than the shoot. As the latter grows to 1–2 cm, the root is already 15–20 cm long and continues to grow. The young seedling of 7–8 cm length may have a primary root of 30 cm in a good soil. A young maize plant extends its roots horizontally in a circle of 90 cm radius. Later, the depth of the root system reaches 200 cm and horizontally 70–100 cm. (*Menyhért* 1985). In the fibrous root system, the primary root is not longer than the other shoot borne roots. The basal part of the primary root is thick for a short length, and becomes thin as the rest of roots.

*The accessory or shoot borne roots* belong to three groups according to their initiation (side roots, crown roots, supporting roots). The side roots start growing from the hypocotyl near the cotyledon and mesocotyl. They grow downwards side by side with the primary root and supply water to the young plant by means of thin branches. The depth of roots reaches 50–100 cm but soon may also extend to 300–400 cm (*Tavćar & Lieber* 1939).

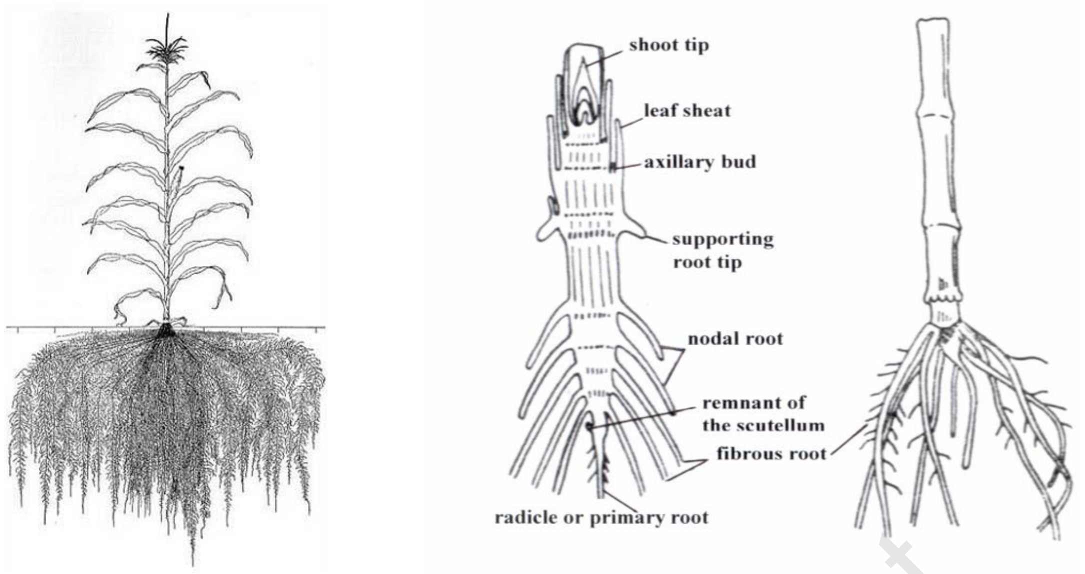

*Figure 2.11* – Longitudinal section of a young maize plant (left) and the basal part of an adult plant (right).
(Source: after *Sachs* & *Rauh*, *Troll* 1954)

The crown roots start growing at successive levels at the increasing number of nodes. The lowermost circle starts from the node of the coleoptile. Those are the so-called epicotyl roots, which start horizontally, then turn downwards. The first of them starts growing as a rule on the side of the first leaf primordium. On the next node, the crown roots grow horizontally and penetrate the upper soil layer, which is most effective regarding the nutrition of the plant. The first crown roots appear at the age of the 2–3 leaves of seedlings at a depth of 3–4 cm on the first node of the shoot. The secondary crown roots, (which are difficult to distinguish from the epicotyl roots) follow each other at 7–8 levels below the soil surface. Their thickness (diameter) increases gradually with each level.

The sizes of roots on the successive nodes were measured by *Troll* (1954):

| Number of nodes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Diameter, mm | 1.0 | 1.7 | 2.5 | 3.3 | 4.2 | 5.0 | 6.8 | 8.0 |

Roots starting from the lower nodes grow in the shallow level of soil at an angle of 15–20 degrees, whereas those from the 5th and 6th nodes grow at 40–45 degrees downwards (*Krakkai* & *Mészáros* 1958). The number of roots starting from one node increases gradually, firstly four and, at the upper nodes, 8–12 roots start from one node. The horizontal as well as vertical extension of the growing crown roots is variable according to the variety, plant density and soil type. Horizontally, the distance may attain 70–100 cm but potentially up to 160–180 cm, which means the roots may overlap the area assigned to the neighbouring plants. The depth may also attain several metres, but the bulk of roots are concentrated in the upper 25–30 cm of soil (*Bocz* & *Nagy* 1978).

The supporting roots start growing on the upper (aerial) nodes of the stem (*Figure 2.12, coloured pictures*). Generally, the 2–3rd aerial nodes of the stem develop roots, but late maturing types may bear roots on the 6–7th nodes. Root primordia on the upper nodes often do not start growing and remain rudimentary. Under favourable conditions, the supporting roots reach the soil, penetrate and develop thin branches, and thus contribute to the nutrition and stabilisation of the plant.

An anatomical peculiarity of maize roots is the abundance of air spaces in the tissues (*Andrejenko* & *Kuperman* 1961). The heavier the soil and the deeper the position of the root, the larger is the air content of its tissues.

The volume of the root system of maize depends largely on the environmental conditions, although the genetic properties are also significant (*Tavćar* & *Lieber* 1939). Varietal differences are expressed also in hydroponics at an age of 21 days of the plant. Small plants have a smaller root system as a rule. The effect of heterosis is expressed in the root system as well; hybrids develop larger root systems than the inbred parents.

### *2.2.2. The shoot system*

The aerial part of the maize plant is composed of the main stem; occasionally branches called suckers, on the ends of growing tips, the male inflorescences or tassels and on the branches the female inflorescences or ears. The shoots develop on each node into one leaf (*Figure 2.13*). Maize is monecious with unisexual flowers developed on the same plant grouped in male and female inflorescences. The main axis of the maize plant is the stalk which supports the leaves. On the axillary branches of the stalk appear the husk leaves and on the top the ear. On the top of the stalk is the tassel.

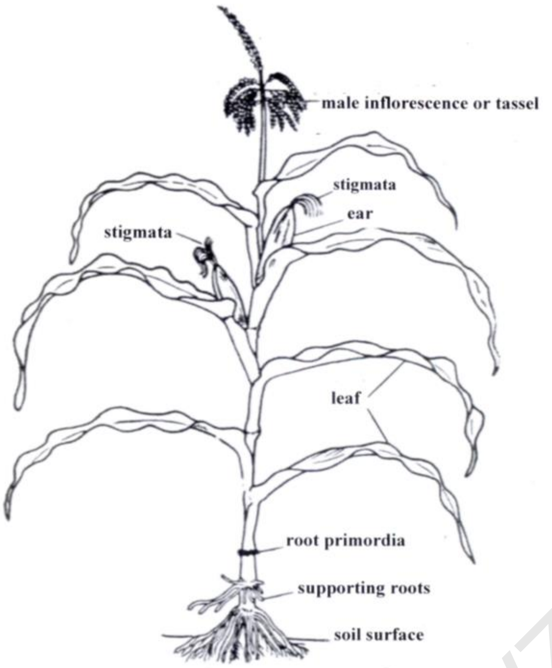

*Figure 2.13* – The classic form of the maize plant. (Source: After *Wallace* & *Bressman* 1949)

The main axis may develop on the lower nodes vigorous branches or suckers. Their number is variable between 1 and 10; they appear often in even numbers (*Tavćar* & *Lieber* 1939). Suckers are rarely produced near to the soil surface. The tendency to grow suckers is a genetically fixed trait. They appear early at 20–25 cm size of the plant, at an age of 1–3 weeks. The flattened main axis shows at both edges from the axillary buds of leaves the leaf tips of the suckers in the plane of the first leaves. The branches develop supporting roots, like the main axis, but they are weaker than the main shoot, although at flowering time they may attain the same height. As a rule, the tassel and silk appear later on the suckers than on the main axis. Suckers may also develop ears, sometimes also instead of tassels or both.

### *2.2.3. The stalk and the leaves*

The stalk of maize is stiff, perpendicular, cylindrical with a filled out pit and articulated by nodes. The length or height and its diameter depend on the variety and on the environment. The final height is between 50 cm and 7 m; varieties grown in Hungary may vary between 120 and 300 cm. The diameter changes gradually: 3–6 cm at the base, 1–2 cm on the top.

The stalk is divided by nodes; the internodes are shorter near the base and longer towards the top. The number of nodes of the main axis varies also according to the variety, between 8

and 40. The lowest 3–10 nodes beneath the soil are close to each other; the aerial 6–30 nodes are more distant from each other. In varieties grown in Hungary, the respective numbers are: 6–7 subterranean and 9–12 aerial nodes. The aerial internodes are smooth, glossy or waxy, with fine longitudinal furrows. The stalks are more or less covered by the leaf sheaths. On the internodes depressions appear in an upwards accentuated order until the ears, subsequently, the depression is gradually reducing and disappears on the uppermost ones. The depressions on the stalk appear alternately corresponding with the leaf sequence of the shoot. On the node under the depression, axillary buds are inserted, the initials of the branches including the branching of the ear. Potentially, each bud may develop into an ear under the cover of the leaf sheath, but depending on the variety, at a set height, only a few (1–4) ears are developed.
The stalk is fleshy, juicy and brittle. Its stability is partially secured by the stiff leaf sheaths. The leaf sheaths hold the increasing weight of the ear until lignification has ocurred. The length of internodes varies. The uppermost is the longest, but the other internodes are variable, but this is also subject to genetic factors. Heterosis effects are also expressed in internode length. During earlier phases of growth, the length diminishes in going upwards, but this tendency is reversed at full maturity.

The leaves are inserted alternately in two rows. The number of the aerial nodes determines their number. Current varieties in Hungary have 9–12 leaves. The longer the growing period of the variety, the higher is the number of leaves. The husk leaves covering the ear are transformed leaves (they will be treated in relation to the female inflorescence). At the appearing of tassels, the first or oldest leaves die.

The leaf is divided into the sheath and the blade (*Figure 2.14*). At the connection of those parts, there is the ligula (or tonglet). The sheath is strongly developed; it surrounds closely the node of insertion and the internode as far as the next node and the lower part of the sheath of the next leaf. The surface is silky but not smooth, sometimes hairy; on some varieties the hairs are very dense. The leaf sheaths contribute significantly to the protection of the female inflorescence and to the stability of the stalk. The leaf blade is long and, depending on the variety, 4–15 cm wide. Its length increases until about the insertion of the first ear, and then declines gradually. At the upper edge of the leaf sheath is the ligula (tonglet), which is a narrow blade of 1–2, sometimes 5–6 mm length with a ciliate or serrate edge. Its colour is darker than the rest of the leaf or whitish. In the middle of the blade a marked light main rib protrudes on the abaxial side of the leaf. Parallelly, 9–17 side ribs follow the main rib. The blade is stiff initially, but later turns in a horizontal position with a drooping tip.

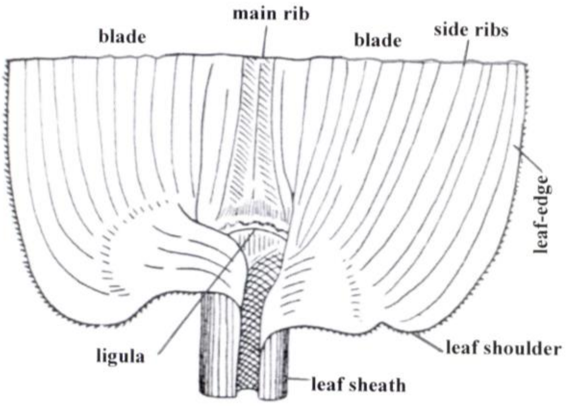

*Figure 2.14* – The basal fragment of the leaf blade and the upper end of the sheath. (Source: *Surányi* & *Mándy* 1955)

The leaf area is an important condition of productivity, therefore its determination is considered from the point of view of breeding and growing technology: *Montgomery* (1911) proposed a formula for its calculation:

$$\text{Leaf area} = \frac{3 \text{ x length of the leaf blade x width of the leaf blade}}{4}$$

It has been shown experimentally that the leaf area of the plant is greater than the soil surface assigned to the plant (*Berzsenyi* 1988b). The leaf area index (LAI) attained the largest values as a result of fertilisation up to 60 kg N/ha. Higher doses, i.e. $N_{60}$, $N_{120}$, $N_{240}$, $N_{300}$ kg/ha did not cause further increase (*Pakurár* 2000), i.e. the value of $LAI_{max}$ did not change significantly. After having compared the curves of yield plotted against the fertiliser and of $LAI_{max}$ plotted against the fertiliser, he concluded that the yield was more sensitive to nutrition than $LAI_{max}$. Most increments of $LAI_{max}$ values occurred between the non-fertilised and the treatment of 60 kg N/ha (*Figure 2.15*).

### *2.2.4. The inflorescence*

Maize is a monecious plant. Although male and female flowers are grouped in separate inflorescences, they are produced on the same plant.

The female flowers are on the ear, a *spadix inflorescence*, which grows from a lateral bud of the main axis or of a sucker, a branch arising from a lower node of the main axis. The ear itself is a terminal structure of a short shoot. Buds of that type appear on each node of the stalk except the 2–4 uppermost ones, but in most dent type varieties grown in Hungary, 1–2 or exceptionally three ears per plant are produced. Among them the upper ear is more developed. In some varieties, which produce several ears per plant, the difference between the ears is less accentuated. The branch of the ear has a short axis and several leaves, which are modified to husks followed by the spadix with the closely inserted spikelets. The axis develops 4–14 short internodes; in current varieties, it is shorter than the half-length of the ear, but sometimes attains 20–25 cm. The internodes are gradually shorter going up the plant and become somewhat lignified at maturity.

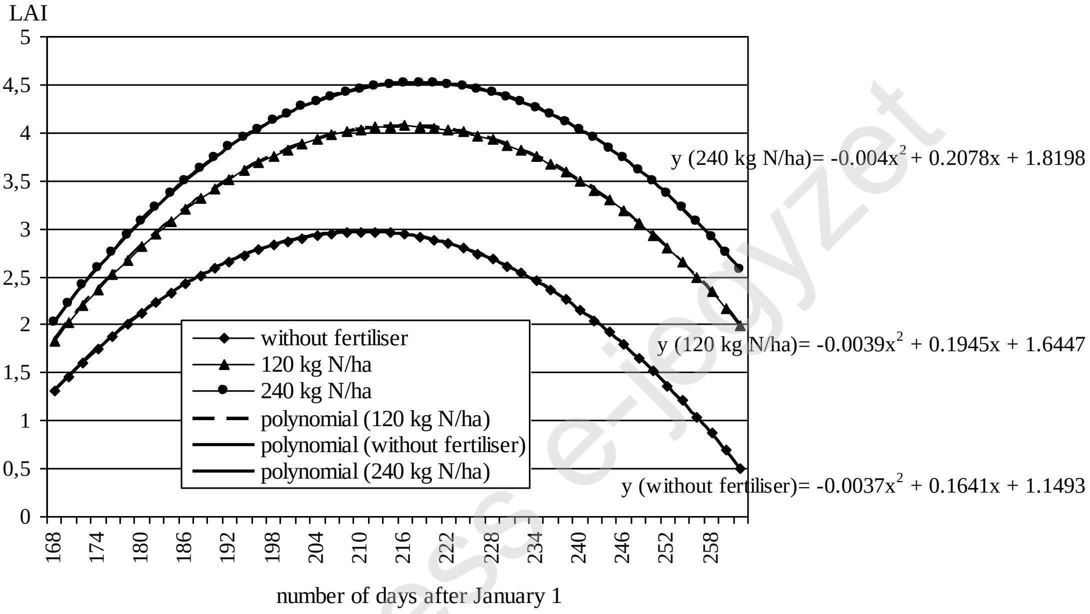

*Figure 2.15* – The changes of LAI at different levels of fertilisation, Debrecen. (Source: *Pakurár* 2000)

The husks are modified leaves, which protect the ear. Morphologically, they have a developed sheath part and a reduced blade, if any. The husks are also inserted alternately in two opposite rows and closely cover the developing ear. Their number is genetically fixed and coincides with that of the nodes, 4–12, mainly 6–8. The lower husks are rudimentary and green, and then the following husks are gradually thinner and paler, while the last ones are film-like and light yellow. The axis of the spadix is fleshy, fibrous with a pit inside. At maturity, the cob is lignified, relatively light and its weight attains 16–25% of the whole ear.

The female inflorescence is composed of spikelets with three glumes and 2–2 female flowers. The current varieties have very small, membrane-like glumes, which are hardly visible at maturity. Glumous varieties have large glumes, which cover the kernels. Within the spikelet are the glumes, rudimentary awns and female flowers in the middle. From the top of the sessile pistil start growing the two, closely fused stigmata. The longest stigmata are found on the flowers at the basal position, the shortest ones at the tip of the ear. The popular, so-called, silks protrude from the top of the husk and are exposed to a length of about 5–10 cm, they are light yellow or reddish, later become brown. Their colour is characteristic for the variety and is mentioned in their description (*Figure 2.16, coloured pictures*).

*The male inflorescence (or tassel)* is on the terminal end of the main axis of the stalk (*Figure 2.17, coloured pictures*). It is a stiff, erect, profusely branching panicle, which tapers upward. The number of branches is variable, 1–20 or more, each of which starts from a node. Each branch bears along its 4/5 length spikelets.

In each spikelet there are two male flowers covered by glumes of green, reddish or purplish colour. Within the glumes are three stamens and two membranous awns. The anthers are either green or purple and hang out between the glumes at flowering. The latter begins following the appearance of the tassels after 3–13 days, with a mean of 9 days. At high temperatures this time span could be shorter by 1–2 days (*Berzsenyi* 1958). The time indicated depends also on the variety as an inherited character.

### *2.2.5. The ear and the fruit*

The maize ear develops from the fertilised (pollinated) female inflorescence, the spadix. The following parts compose the fresh, harvested ear: husks, pedicel, cob, silk remnants and kernels. Length, width and volume of the cob are properties of the variety and are influenced by the environment, moisture, and nutrition and planting density. The length varies between 3–50 cm, the width 2–10 cm, and the volume 25–700 g. The dry husks are leathery and have considerable tensile strength. The husks may become yellow or bleached. The short internodes of the pedicel are lignified. The length of the pedicel is a varietal property though highly influenced by the environment. The dent type varietes have longer pedicels than the hard maize varieties. The pedicel continues immediately in the cob. The cob is cylindrical slightly tapering as the axis of the conic spadix. The ripe cob is a stiff, lignified construction. Its colour is white, red, or purplish red. Inside there is the parenchymatous tissue of the pit. Its width varies between 0.5–8 cm. *Remnants of the stigmata* are not significant any more. The silk is then light or dark brown. Its role may be the protection of the top of ear from bird damage.

The maize kernel is the fruit grown after pollination of the pistil of the female flower. It is in morphological terms, a dry fruit with one seed inside, where the pericarp is closely fused with the testa (or seed coat). The size and form of the maize kernel is very variable according to varieties. Intervals of length are 2.8–23 mm, and of width: 2.7–18 mm.

The most common form of kernels in the dent type varieties is a flattened wedge shape, but the kernel forms of other varieties are extremely variable (round, oval, kidney shaped, like a rice grain, etc.); similarly, the colour of the kernel is also variable. The most common colour is yellow but between white and black many variants exists. The colour of the kernel results from the colour of three layers, the pericarp and the outer and inner layer of endosperm tissues. The flat maize kernel is smooth on the dorsal side and shows a long, oval shaped depression (furrow) on the ventral side, where the germ is underneath. The kernels are located on the ear with the ventral side turned towards the tip of the ear and the dorsal side to the base. The germ is located parallel to the axis of the kernel along the ventral depression. The radicle toward the base, the shoot towards the top, between them the scutellum are distinct. The germ represents 8–15% of the kernel volume. The most important component of the kernel is the *germ*, which will become the young plant after germination.

The arrangement of the kernels on the ear may vary depending on the type of variety: either in regular rows parallel to the main axis of the ear, or spirally running rows, or irregularly. The first variant is preferable. The number of rows per ear is 4–40, most frequently 8–24 as in the current varieties. The number is even, and often the multiple of four. The form and size of the kernels varies depending on their position on the ear. Near the base the kernels are more stout or round, at the middle part regular and flattened, near the tip again more irregular. Near the base the kernels are larger and gradually become smaller towards the top.

Taking the kernel at the middle of the ear as standard, the basal kernels are larger i.e. have a thousand kernel weight 7–14% greater, whereas near to the tip the thousand kernel weight is 24–18% smaller (*Surányi* & *Mándy* 1955, *Bajai* 1958, *Antal* 1962*)*. The more ears are borne on the plant; the lower is the length, volume and number of kernel of ears (*Surányi* 1957). Under favourable conditions, the second ear is also fully ripe at the same time, though smaller. The number of kernels per ear is enhanced by fertilisation rather than by irrigation (*Figure24.18*). Studying the parameters of ears in field experiments *Nagy* (1978) stated that under non-irrigated conditions, the ears were 20–23 % longer due to fertilisation compared with the non-fertilised treatment. Under irrigated conditions, the fertilisation did not influence the substantially the ear length.

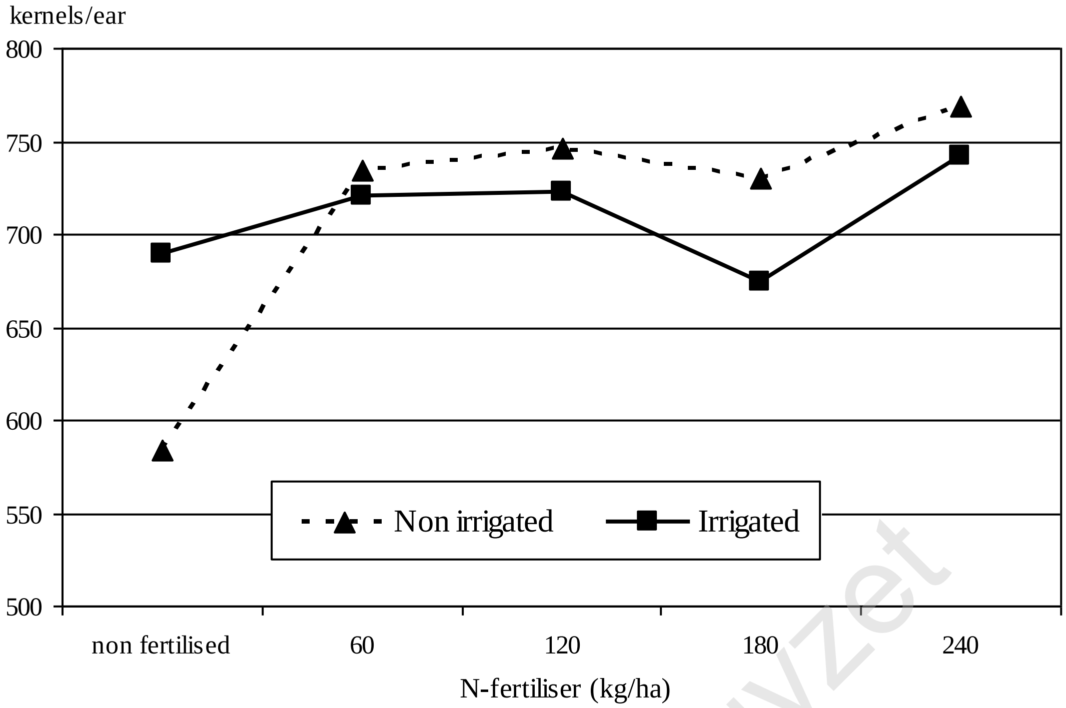

*Figure 2.18* – Effects of fertilisation and of irrigation on the number of kernels per ear. (Source: *Nagy* 1978)

## 2.3. Development of the maize kernel

The development of the kernel starts soon after pollination and subsequently fertilisation. Following pollination the fertilised egg cell is transformed to a diploid germ cell and starts dividing within one or two days. On the fifth day, the germ and the suspensor are easily recognised whereas on the tenth day the shoot and scutellum are distinct. On the 12th day, the first leaf rudiments appear and on the 14th day the radicle. On the 30th day, five leaf primordia can be recognised. Subsequently, the growth of the germ becomes more rapid until the 45th day, when the germ is fully developed. In parallel, the endosperm gradually proliferates.

### *2.3.1. Germination*

*The conditions of germination.* Moisture, adequate temperature and oxygen are needed for germination. To begin with, water is taken up by the kernel tissues and this triggers the process. *Toole* (1924) distinguished three phases within the process of germination: 1. the soaking of the kernel with water, 2. the elongation of the existing cells and 3.the start of cell division in the meristems. There are minor differences between the water uptakes of some hybrids. Kernels containing originally 15% moisture are soaked at the same rate during the first 24 hours. Kernels with less than 15% moisture content take over the difference within 24 hours (*Surányi* & *Mándy* 1955). Water uptake continued after the 48th and the 96th hour as well with 7–8%. Most water was taken up by sweet corn varieties, in which it attained 90% of the dry weight of the kernel (*Huelsen* 1954), other types took up water to a proportion of 50–70% (in 96 hours). Kernels, which were exsiccated when immature, took up more water than the ripe kernels. The majority of water penetrates through the basal part of the kernel.

The other condition of germination is the correct temperature. The limits of temperature necessary to start germination of kernels are rather wide. In the field, a soil temperature of 8–12 °C is considered as a minimum although *Andrejenko* & *Kuperman* (1961) claim that germination starts already at 6 °C. At that temperature however, the growth of the germ is too slow, and the plant is susceptible to pests and pathogens. According to *Surányi* & *Mándy* (1955), germination is influenced by soil temperature: at 21 °C, the seedling emerges 5–6 days after planting, at 16–18 °C, after 8–10 days, and at colder temperatures, only after 18–20 days.

*The process of germination and the development of the seedling.* Firstly the kernels swell with the water taken up. At a suitable temperature, 30% water initiates the growth of the germ. The furrow of the ventral side of the kernel disappears, then the pericarp tears longitudinally and from the fissure the radicle covered by the coleorrhiza emerges. The radicle turns downwards, whereas the shoot within the coleoptile turns upwards if there are no obstacles. Between the radicle and the shoot the mesocotyl swells and, on the fourth day, the adventitious root primordia appear. The germ is nourished across the scutellum by the endosperm. The young germ rapidly becomes independent, which is demonstrated by the elimination of the rest of the endosperm without deleterious consequences to its growth.

As for the germination process, we have to distinguish germinability (germinative ability) from the germinating vigour, the latter means the speed of the process. Germinability is expressed by the percentage of germinating seeds within a set time (16 days). Germinating vigour is characterised by the percentage of germs appearing four days after the beginning of germination. As the speed of the process depends largely on the conditions of moisture and temperature, the test of germinating vigour needs strictly set conditions.

The difference in results between laboratory tests and field conditions used to be considerable; the colder the soil temperature, the larger was the difference. Laboratory tests used to be performed at optimal conditions of moisture and temperature. Moreover fungi are ready to attack the germinating seeds. The same pathogens are usually harmless under sterile laboratory conditions. For that reason, a “Cold test” was introduced in the USA in the 1920s. The essence of the test was that the seeds are held in moist soil for 7–10 days in cold (6–8 °C) temperatures, and then subsequently they are transferred with or without the soil to near-optimal temperatures.

If the germinating seed is put into dry soil, it quickly dies. That is the risk of using pregerminated seed. If the soil gets cooler than 6–8 °C, the growing process stops or slows down in spite of the temperature minima of the roots are lower than those of the aerial parts. The delayed emergence of too early plantings is often experienced. The first leaves only appear after the splitting of the coleoptyle 1–2 cm above the surface.

The seedling is susceptible to certain compounds. Superphosphate granules may damage the maize seedlings and herbicides containing mercury are deleterious.

Some seed treatments shortened somewhat the time needed for emergence – as a mean of three planting dates – using two compounds for treatments (*Záborszky et al.* 2001). The percentage of emerging seedlings proved clearly the utility of seed treatments (*Table 2.1*).

*Table 2.1* – The effect of seed treatment with different compounds on the parameters examined as a mean of planting dates, soils and genotypes

| Compound used for treatment | Time of emergence (days) | Emerging plants (%) | Dry matter content (mg/plant) |
|---|---|---|---|
| Kaptan | 18.40 | 92.10 | 33.71 |
| Check | 19.17 | 74.90 | 23.90 |
| Carboxin+TMTD | 18.42 | 96.30 | 33.64 |
| SD5% | 0.15 | 2.89 | 1.08 |

Source: *Záborszky et al.* 2001

### *2.3.2. The role of the root system in nutrition of the maize plant*

Physiological experiments show that the root system is not only an apparatus for performing the uptake of water and nutrients from the soil, but it is also the site where mineral substances are transformed to organic compounds for the living organism (*Végh* 1992, *Végh et al.* 1996). In hydroponics, under sterile conditions, maize plants having been deprived of their aerial organs were able to build P32 isotope into organic compounds. Similarly, nitrogen is also incorporated at a considerable quantity in the roots. Several amino acids are present in the guttation fluid of maize stalks especially in the generative phase of developent. The ability of roots to assimilate inorganic substances is also evident with inorganic sulphur, which appears in methionin and glutathion (*Bergmann* 1993, *Römheld* 1993, *Füleky* 1999).

*Environmental effects appearing in the development of the root system.* Several researchers explored the physical components of the environment being decisive for the growth of roots. The structure and the size of granules of the soil (*Gras* 1961), the porosity (*Maertens* 1964), the salt content and alkalinity (*Moulinier* & *Mazover* 1968) and water content (*Thorup* 1969) have been analysed. If the individual components do not attain sufficient rates, they impair also the effects of other environmental factors. Amongst the environmental factors, certain effects of light and temperature (climatic conditions) stimulate the growth and root development (*Kleinendorst* & *Brouwer* 1965, *Brouwer* & *Dewitt* 1969).

*The planting depth and the formation of the root system.* The idea was often proposed that the deeper the seed was located, the better will the plant resist drought. *Krakkai* & *Mészáros* (1958) experimented over three years with this relation on roots of 15–46 plants:

| Planting depth (cm) | 3.5 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of crown roots | 2 | 2.3 | 3 | 2.9 | 3.1 | 3.6 | 3.9 | 4 | 4.1 | 4.1 |

With the depth of planting, the position of crown roots was but hardly influenced. The germinating plant used to elongate its first internode, the mesocotyl, consequently, the crown roots start growing howsoever at a depth of 3–4 cm. Notwithstanding, the position of the root system is largely determined by other circumstances (e.g. irrigation) than by their sowing depth. Seeds at 8–10 cm depth develop crown roots almost at the same position as those in shallow plantings. Deep planting is intended to lower the risk of exsiccation and secure more uniform emergence.

*The effect of irrigation on development of the root system.* The main effect of watering is a more shallow penetration of roots. This ensues for two different reasons. Firstly, the roots need not seek areas of higher moisture and, secondly, the water soaked soil contains less oxygen than nearer to the surface. In non-irrigated soil, six weeks after planting roots may reach 30–60 cm depth, whereas in irrigated soil 15 cm only. The branching of the roots is also influenced. In moist soil, five branches per cm start on the main root, whereas in non-irrigated soil 10–11 branches. *Nagy* (1978) checked the root mass of maize at three levels of nutrition.

The upper 25 cm layer of soil harboured from 88.9 to 96.5% of the whole root mass. Under irrigated conditions and higher levels of nutrition, the upper 0–25 cm layer contained 79.3% more roots than the control (1.416 t/ha) (non-irrigated) treatment. Higher doses of fertilisers reduced root mass by 48.2% in the 25–50 cm soil layer (*Table 2.2*). The roots are concentrated in the upper 25 cm soil as a consequence of a favourable supply of water and nutrients; on the contrary, root growth was displaced rather to deeper layers of the soil.

*Effects of fertilisers on the root system.* The primary effect of nutrition appears on the roots and then passes to the aerial parts as a stimulation. As a side effect of N fertilisers, the roots remain shorter, but develop more branches. The upper layer of the soil becomes covered with a dense network of roots. Nitrogen enhances the activity of cells and the branching of roots. Phosphorus, on the other hand stimulates the longitudinal growth of roots and the development of root hairs, such that P fertilisers could be called specifically root-fertilisers.

*Table 2.2* – The distribution of the root mass modified by fertilisation

| Treatment | Root mass (t/ha) |
|---|---|
| *0–25 cm soil layer* | |
| Non-fertilised | 1.785 |
| 120 kg N+90 kg $P_2O_5$+106 kg $K_2O$/ha | 2.307 |
| 240 kg N+180 kg $P_2O_5$+212 kg $K_2O$/ha | 3.201 |
| *25–50 cm soil layer* | |
| Non fertilised | 0.220 |
| 120 kg N+90 kg $P_2O_5$+106 kg $K_2O$/ha | 0.162 |
| 240 kg N+180 kg $P_2O_5$+212 kg $K_2O$/ha | 0.115 |

Source: *Nagy* 1978

As an effect of N fertilisation, the mass of the root system increases (*Haas* 1958, *Goetz* 1969). *Eghball et al.* (1993) also showed the morphological effect of N stress on maize roots. At the site where the nitrogen touched the root, longitudinal growth was stimulated; however, the entire length of roots was invariable (*Derieux et al.* 1994). Among the climatic factors, above-optimal temperatures reduced the mass of roots. Increasing doses and the ammonium form accentuate that type of effect (*Stoin* 1968). *Khanna et al.* (1974) explored the density (mass/volume) of sandy loam on the uptake of phosphorus and activity on the roots. The compaction of soil inhibited P-uptake as well as the root activity especially in the deeper region. Between the two parameters, there was a close correlation.

Planting density and row distance modify the development of the roots. Studies of *Krakkai & Mészáros* (1958) at Gödöllő dealt with the effects of two planting designs: (260 + 40 x 40 cm) and (70 x 70 cm). In the former, twin-row system, the crown roots of maize often grew horizontally beneath the surface for a distance of 160–180 cm, i.e. overlapped the roots of the neighbouring maize row (at 260 cm) by 30–50 cm, whereas the roots grew horizontally for 70–90 cm in the 70 x 70 cm design, and then turn downwards at a steep angle.

The depth of the tillage is also decisive from the point of view of rooting especially under arid conditions. *Varga* (*Ruffy*) (1929) performed studies at Debrecen, and stated that after deep ploughing the depth of rooting attained 183 cm, whereas in deeply overturned soil roots were found at 365 cm. Precipitation was an influencing factor because, in a rainy season, roots may find enough water in the upper 15–20 cm layer of the soil and do not penetrate deeper. On the contrary, a dry season stimulates deep rooting, which was observed also when the second part of the season was dry and the roots followed the moist layer.

Roots near to the surface utilise the summer showers, which penetrate into the soil (5–6 cm) and are considered as an important source of water. *Krakkai* & *Mészáros* (1958) observed at Gödöllő in the twin-row system that about 0.5 metre from the rows there was a strip where the water dripped from the leaves and where many more roots were found than elsewhere near to the surface.

### *2.3.3. Growth and development of the shoot system*

*Shoot growth and development at an early stage of shoot growth.* The growth of the main shoot is highly influenced by temperature, soil moisture and genotype. The longitudinal expansion of the shoot is at the beginning much slower than of the root in spite of optimal temperatures. Sachs showed it first according to *Surányi* & *Mándy* (1955) as measurements of the shoot and the rootlet of a germinating seed were compared after a period of 48 hours:

| | | | | | | |
|---|---|---|---|---|---|---|
| Temperature ($^{o}$C)˙ | 17.1 | 26.2 | 33.2 | 34.0 | 38.2 | 42.5 |
| Rootlet (mm): | 2.5 | 24.5 | 39.0 | 55.0 | 25.2 | 5.9 |

Shoot (mm): 0.0 5.6 11.0 13.0 9.1 4.6

This relation is even more conspicuous at low temperatures, which often occur during the springtime. Temperature minima and optima of the shoot are always higher than those of the root. The minimum of the shoot is about 6–8 °C, and of the shoots 4–5 °C.

*Growth of the shoot.* The speed of elongation increases in the field at the 3–5th week after emergence, depending on the variety. Most of the varieties stop growing at the end of July or early August. Elongation is associated with the development of different organs. In Hungary, the volume of the increasing organs of maize has been traced by *Ferencz* (1958) and *Mándy* (1962). They stated that the volume increased rapidly until the middle of July, subsequently gradually until early September, whereas the growth of the plant slows down until reaching its final volume within one month. The dry mass is then about equal to the fresh weight at the middle of July. Until then, the growth of the stalk dominates; afterward the growth of the ear prevails. The accumulation of dry matter follows a different pattern. The increment in total dry matter is linear and parallel with the dry matter of the ear. The growing volume of stalk and foliage continues by one month beyond that of the fresh volume.

The speed of growth of the maize plant depends not only on the inherited properties of the variety but also on the growing site, its climate and weather. *Mándy* (1958) followed up the growing dynamics of 11 varieties and observed an ample variation among the weekly maxima of varieties. Fertilisation exerted a positive effect on growth (*Nagy* 1978) and the latter was correlated with the dose (*Figure 2.19*).

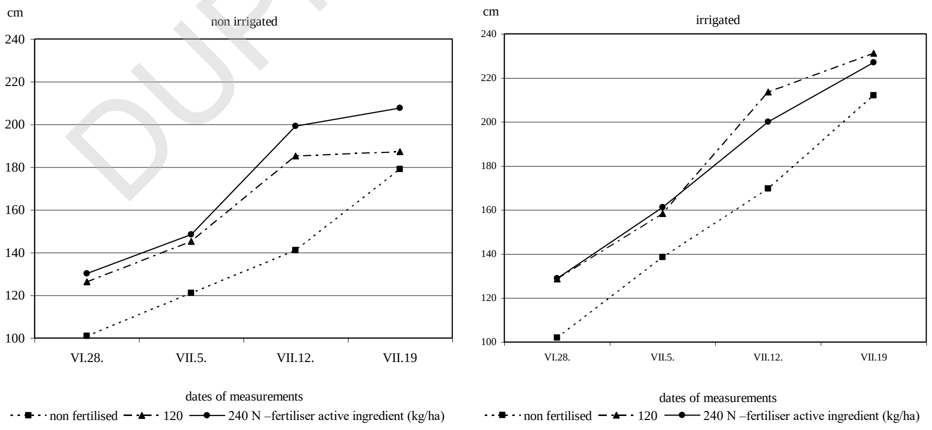

*Figure 2.19* – Growing rates of maize under different conditions of irrigation and fertilisation. Debrecen.

(Source: *Nag*y 1978)

Under various weather conditions, the height of the plants differed (*Bocz* & *Nagy* 1981). *Schuster et al.* (1979) stated that all hybrids observed grew more rapidly under short-day conditions. They also observed that the growing period doubled at lower (14 °C) temperatures in comparison to higher (15 °C) temperatures. The prediction of the daily increment of growth is necessary from the point of view of knowing the time when tassels are expected to appear, let alone the length of the growing season (*Neild* & *Seeley* 1977). Higher yields are significantly positively correlated with the length of the stalks as well as of the ears (*Georgiev et al.* 1979). The rate of growth at the 5–6 and of 9–10 leaf stages in the hybrids is not associated with kernel yield; however, the final size of the plant was observed to be positively correlated with it (*Vedenev* 1982). In some experiments, the planting density was not decisive in determining the length of stalks (*Gagro* 1974). On the contrary, *Kising* (1962) demonstrated a positive effect of planting density and the length of stalks in an experiment with 20, 30, 42, and 61000 plants per ha treatments.

Optimum values of the leaf area index (LAI) has been determined according to *Menyhért et al.* (1980) to be about 4.1–5.9 $m^2/m^2$. Genotypes differed from each other regarding their LAI optima. *Dang* (1993) observed a close correlation between the values of LAI and yield, moreover, that the most up to date hybrids display high LAI values as well as high Leaf Orientation Values (LOV). During the growing period, the leaf area of the plants grows continuously until the lower leaves start to die. The correlation between yield and the maximum of leaf area is close (*Lönhardné* & *Németh* 1989). The leaf area depends on nutrition, especially on the supply of nitrogen (*Nagy* 1978). An initial rapid increase in leaf area and later the maintenance of an optimal LAI is closely dependent on delaying the process of senescence by thoughtful N fertilisation (*Berzsenyi* 1988a). For the purpose of determining the extent of N deficiency, the speed of growth and the measurement of LAI are the most suitable methods (*Berzsenyi* 1988b). According to *Anda* (1987), increasing N supply is the cause of significantly higher LAI, longer stalks, moreover, higher yields until $N_{200}$. *Berzsenyi* (1993) considers the importance of N nutrition through its effect on increasing leaf area and on its maintenance at an optimal level. The LAI signals the growth of plant populations at different levels of nutrition. In experiments of *Ruzsányi* (1974), the leaf area of maize hardly changed as an effect of fertilisation, whereas the relation between the leaf area and water consumption was clearly logarithmic.

*The nutrition of the suckers.* Earlier, it was believed that the suckers are competing with the main shoot; therefore, they are deleterious to the yield. The role of suckers in the physiology of the plant has thus been studied purposefully.

At Martonvásár, the experimental plants deprived of their leaves on the main shoot yielded solely from the organic products of the suckers. The volume of the ears, of the kernels, the thousand-kernel weight, and the shelling rate of the ears was entirely the product of the suckers. That means that the suckers contributed significantly to the yield (*I'só* 1959). Similar American and Hungarian experiments show the positive effect of suckers on the nutrition of the main shoot. The same results have been obtained by experiments examining the content of guttation and by applying radiating isotopes. The mineral nutrition of suckers benefited also the main shoot (*Dévay* & *Gáspár* 1958). On the hybrid *Martonvásári 5* grown in the field, it was shown that the suckers did not reduce the yield of the main shoot.

Experimental defoliation as well as nutrition-physiological approaches demonstrates the role of suckers in the uptake of nutrients as well as their activity in assimilation of organic substances contributing to the development of the main stalk (*Győrffy et al.* 1965).

*The regeneration of shoots.* The physiology of the maize shoot is closely interested in the consequences of damage caused by frost and hail, which affects the capacity for regeneration. The less developed the plant, the heavier the damage caused by frost. American studies (*Shaw* 1955) stated that the young plant is relatively resistant, i.e. it dies at about –1 °C. According to other sources, –1.7 °C is deleterious to young plants, but –4.4°C is lethal. Some inbreds and hybrids may suffer but tolerate –4 °C, whereas others die. In Iowa 1947, a late frost of –0.5 °C killed the aerial parts but the maize plants soon recovered.

In Hungary in 1952–1953, there were frosts during May (–3 - –6 °C). According to the assessments, the aerial parts of young maize plants were damaged at –1 or –2 °C, but recovered. At that time, the growing point of the regularly planted germinating plant is still below the soil surface. Lower temperatures (–3 - –5 °C) during several nights killed the plants. It seems evident that young plants become chlorotic but are relatively more resistant than plants nearer to maturity, when the living processes slow down and the leaves become dry. American reports indicate that many inbred lines die below +7 °C at that period. In another experiment the longitudinal splitting of leaves, which happens often as a consequence of hail, did not result in loss of yield provided the stalk was not scarred. Otherwise, yield was reduced by 23–27%. Among hybrids, there was no significant difference from the point of view of yield losses due to leaf damage.

After frost damage in the spring, the ploughing up of the maize field should not be hurried because the growing point of the germinating plants may remain alive below the surface and the plants able to recover as the root system may be quite advanced (*Varga & Varga-Haszonits* 2003). The severity and frequency of frosts may cause different degrees of damage. A “chill” may ensue at temperatures above freezing point but that is not a serious damage. The young plants are more resistant to high temperatures. At the time of the appearance of tassels and silk, three hot days (with maxima about 38 °C) may jeopardise the development of kernels with up to 70% of losses, and from that point of view maize is much more susceptible than sorghum, which has otherwise a much similar nature.

The most important climatic risk to the maize plant is hail. Tasseling time is the most risky period. Earlier the recovery may compensate for much of the damage, but then the ability of the plant to do so diminishes, whereas the damage caused by hail gradually loses its importance towards maturity. The measure of hail damage depends of course on the density of the precipitation and the force of wind associated with it. A mild wind and light hail only split the leaves and the yield is much less reduced than believed earlier. A strong wind with dense hail may annihilate the whole crop around the time of tasseling. In the USA, a couple of experiments have been performed by simulating the leaf damage by defoliation at different phases of the growing season. According to the results, 25% defoliation caused a 10% reduction in yield at any time except the milky phase of maturity. Maize was most susceptible when 40% of the tassels appeared. At that time a total defoliation (100%) may destroy the whole yield. Leaf splitting at the same time caused 16–43% reduction, breaking the main rib of the leaves about 20% reductions. *Bauman* (1960) stated that defoliation reduced mainly the development of the second ears. The elimination of four leaves reduced the volume of the first ears by 10% only, while that of the second ears dropped to one-sixth of their level in undamaged plots.

In Hungary, *Czakó* (1962) and *Pintér* & *Kálmán* (1979) purposefully caused wounds on leaves and stalks on the plants of the hybrids bred at Martonvásár in order to simulate hail damage. Leaf mutilations of different extents were made at various phases of development. It was concluded that the period of tasseling was most susceptible regarding reduction of the leaf area. In another experiment, leaf splitting and stalk scarring were combined at tasseling and at the milky stage of maturity. The results show that leaf splitting alone was hardly harmful, but combined with stalk scars 23–27% loss of yield was recorded.

### *2.3.4. Flowering of maize, inbreeding and heterosis*

The flowering of maize starts at different dates on the maize plant. As a rule, male flowers start to flower earlier than the female flowers. Less frequently, female flowers precede the start of male flowering. Protandry (when male flowering precedes female flowering) may last 1–8 days, with 2–3 days as a mean (*Berzsenyi-Janosits* 1958). The length of the whole period of male flowering depends on variety and on weather, especially on temperature and varies according to the individual plants. It lasts between 3 and 13 days, with 6–8 days as a mean. Female flowering or silking lasts about 10–11 days. Because of the protandry of 2–3 days, the opportunity for self-pollination (selfing) of individual plants lasts 4–5 days only.

*Flowering.* Flowering of the male flowers may start, in warm weather, within 1–2 days after the appearance of the tassels from the leaf sheaths. But generally 3–13, or as a mean 9, days elapse until full flowering ensues. The first flower opens on the main axis of the tassel and is followed by the flowers on the branches in a sequence from top to bottom. Flowering starts each day in the morning – depending on the temperature – at about 7–9 am and continues until noon. Flowering means that anthers appear between the glumes, split at the distal end and let the pollen grains disperse. The diameter of the round pollen grains is about 110 microns.

The start of flowering of female flowers is observed by the appearance of stigmata (called vulgarly Silk) on the tip of the husks covering the ear. First the stigmata of the lower third of the ear are visible, and then those of the upper flowers follow gradually until the tip of the ear. The time between flowerings of the lower until the upper flowers may take about 10 days. The pollen grain adhering to the stigma soon develops a pollen tube, which grows about 1 cm per hour towards the ovary. That means a stigma of 10–15 cm length will be penetrated within 10–15 hours and the fertilisation of the egg cell in the ovary ensues. If no pollen reaches the stigma, it keeps growing and loses its viability only after 10–14 days. Also the stigmata of fertilised flowers become dry and brown at that time.

Comparing the flowering time of male and female flowers, we see that self-pollination (selfing) of maize flowers is possible. In spite of that, selfing occurs at a low rate in the field. *Berzsenyi-Janosits* (1958) claims that its probability is about 1–2% only while *Andrejenko* & *Kuperman* (1961) estimate rates of 5–7%, sometimes 10%. Self-pollinated flowers produce inbred progeny, which are less vigorous, grow slower, yield less and are less competitive. By artificial selfing we may perform inbreeding, which is repeatedly used over several generations to develop inbred lines. Those exhibit inbreeding depression, which is manifested first of all in the reduced size of plants, which get substantiallysmaller especially during the first four years following self-pollination and continue at a slower rate until the sixth generation. After reaching a minimum, no further reduction is expected by inbreeding. Yield follows the same reduction during the inbreeding process even beyond the sixth generation.

Inbreeding is manifested at the same time in increasing uniformity, which is especially conspicuous after reaching the minimum of growth in the 5–6th generation, but is recognised even in the second or third generation of inbreeding. At the same time, the inbred lines derived from the same open pollinated variety may still differ markedly in several properties, leafiness, form etc. after the 4–5th generation. Those characters are surely fixed and transferred by outcrossing to other lines.

*The effect of heterosis.* Two inbred lines which manifest inbreeding depression are used as parents for crosses, which recover the original vigour, height, fertility and yielding ability, being even superior to the original varieties, in addition to a perfect uniformity of the individual plants. The vigour of the first generation ($F_1$) is utilised in the commercial hybrids of maize production. The following generations, which arise by open pollination ($F_2$, $F_3$, etc.), however, lose the vigour and the uniformity manifested in the $F_1$ generation. Similar heterosis, but of much lower intensity and uniformity is experienced if different open pollinated varieties are crossed. The phenomenon of heterosis and its utility are commonly known but its physiology and genetic mechanisms have not been entirely explored. Maize breeding owes its successes and prosperity to the detection of heterosis, which has been utilised also in breeding of other plants.

*The phenomenon of xenia.* If different maize varieties are grown near to each other, spontaneous hybrids may arise by mutual cross-pollination. With the double fertilisation, the egg-cell as well as the central nucleus of the embryo sac each fuse with one of the two nuclei of the intruding pollen tube. The fertilised egg cell grows to a new plant, the germ, whereas the central nucleus grows to produce the endosperm, the inner nutritive tissue of the kernel, thus it is also a hybrid tissue, whereas the other tissues, the testa and the pericarp are solely of maternal origin. If a variety with white kernels is crossed with a variety with yellow kernels, on ears of the white variety all hybrid endosperms will be yellow because the yellow colour is dominant and the pericarp, as maternal tissue, is transparent. This phenomenon is called xenia, which means that on the maternal plants signs of the pollinator plants appear. The phenomenon of xenia is not restricted to the colour of endosperm, but it is evident e.g. on the ears of sweet corn and dent corn appear the kernels, which contain hybrid germs derived from pollination with smooth kernel varieties, as smooth kernel is a dominant trait.

### *2.3.5. The dynamics of uptake of mineral nutrients*

On the 14th day after emergence, the maize plants has four leaves, the root system is already much more developed, with branching of roots and root hairs. The growing tip of the shoot has started differentiation; rudiments of leaves, husk-leaves and tassels have appeared already. This is controlled by daylength. The roots ought to be protected from damage caused by mechanical soil loosening. The plant needs nutrients, which are taken up by the root system.

During the development of the 8–11 leaves, the stalk grows longitudinally in parallel with the root system. The lower, first leaves gradually die. The tassel develops quickly within the multiple cover of leaves. At that time, a lack of nutrients will inhibit the growth of leaves and may reduce the yield by 10–20%, so fertilisation may become very effective.

After the appearance of tassels, maize plants start flowering within five days, and silks and the stigmata will appear within 2–3 days. This period is the most critical from the point of view of water supply and nutrients. If half of the leaf area were destroyed, 25–30% of the yield would be lost. Among the mineral nutrients, the uptake of potassium approaches its final phase but the uptake of phosphorus and nitrogen is in ful progress. At that time, the expected yield may be predicted on the basis of the size of the leaf area.

With the development of husks and the stem of the ears, the formation of kernels takes a new impetus and accumulates starch and dry matter. An intense P and N uptake and a translocation towards the kernels are in progress. Any lack of water and nutrients increases the percentage of empty kernels.

At the time of physiological maturity, the accumulation of dry matter is complete, the loss of moisture starts in the vegetative parts and the green leaves start yellowing. Dry matter and the volume of ears increase along a steep curve from organs of photosynthesis towards the ckernels. Under favourable conditions, the yield of dry matter is 245 kg/ha/day, which is produced by 2048 kg leaf volume. If the P-supply is short, the ratio is 204:1193, K-shortage 200:1237, if the N is deficient 82 kg dry matter/ha/day is expected with 957 kg/ha leaf volume (*Debreczeniné* 2005). The peak of dry matter production is achieved around early August. The dynamics of dry matter accumulation and the uptake of mineral nutrients are presented in the whole plants and in the organs in *Figure 2.20*.

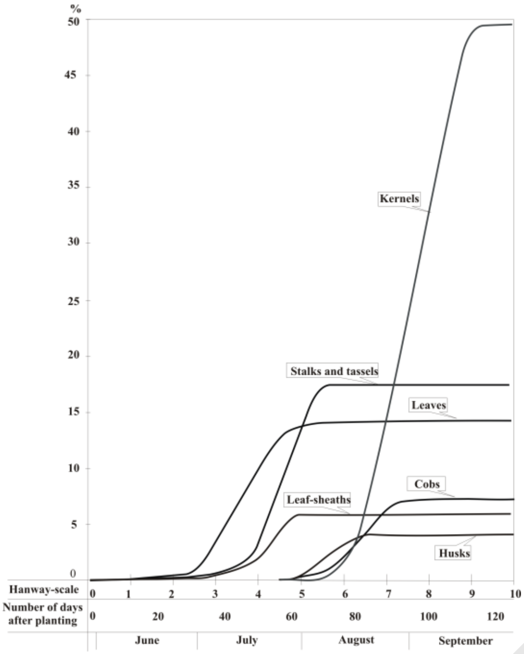

*Figure 2.20* – Accumulation of dry matter content in maize plants. (Source: *Nagy* 2006)

The uptake of nutrients by maize is slow at the beginning, but it is important to supply the plants with available NPK-fertilisers. With the comparison of nutrient uptake and accumulation of dry matter, it was stated that at the end of June, the volume of dry matter in a plant contains about 4%, phosphorus 9%, nitrogen 10%, potassium more than 14%, whereas at the end of July, dry matter is 45%, phosphorus 57%, nitrogen 66%, potassium 92%. These data reveal the seasonal uptake of nutrients in maize. Most of the hybrids may develop kernels over almost 60 days, but there are many varieties, which could do the same during a much shorter period, i.e. 35 days. During the development of kernels, a daily 3% increment of organic dry matter content is expected. Those maize hybrids should be preferred which develop their kernels during a period of 50–75 day because yields could be increased substantially provided the long growing period does not impair the yield.

### *2.3.5.1. Dynamics of nutrient uptake*

*Nitrogen*. At the time of germination, N-uptake is not too high but it is very rapid because the protein content of the seed is just mobilised, which stimulates the uptake of mineral nitrogen. The uptake of nitrogen is more rapid than that of phosphorus until July, but continues until maturity. From the appearance of tassels, during the development of kernels until full maturity, a favourable N supply is of outstanding importance. At sufficient moisture and N supply, the flowering process may start earlier by 2–3 days. Excessive N supply may prolong the time interval between the flowering of male and female flowers. A 30 day-old maize plantation takes up from the soil 3.8 kg N/ha, at age of 40 days 16.5 kg N/ha, at blooming time 4.4 kg/ha. Total N uptake at low N supply (with 6.46 t/ha dry matter volume) was 35 kg whilst at favourable NPK supply (with 17.2 t/ha dry matter volume) it was 198 kg N (*Arnon* 1975). N supply can be checked by leaf-analysis; at 6-leaf stage 4.7% N content is considered to be optimal from the point of view of yield. *Kádár* & *Elek* (1977) claimed that at this age the N supply is poor if it is only 3.5%, sufficient between 3.5 and 5.0%, and excessive above 5%. N uptake depends also on its chemical binding in the soil, on moisture and on the supply of P and K. A favourable N effect is basically a function of adequate presence of P and K, moreover, the ratio N:P influences the time of flowering as well as the size of the kernels. At the process of maturation, 2/3 of the N is concentrated into the kernels. About the half of it will be translocated from the N supply located earlier in the shoot system of the plant (*Figure 2.21*).

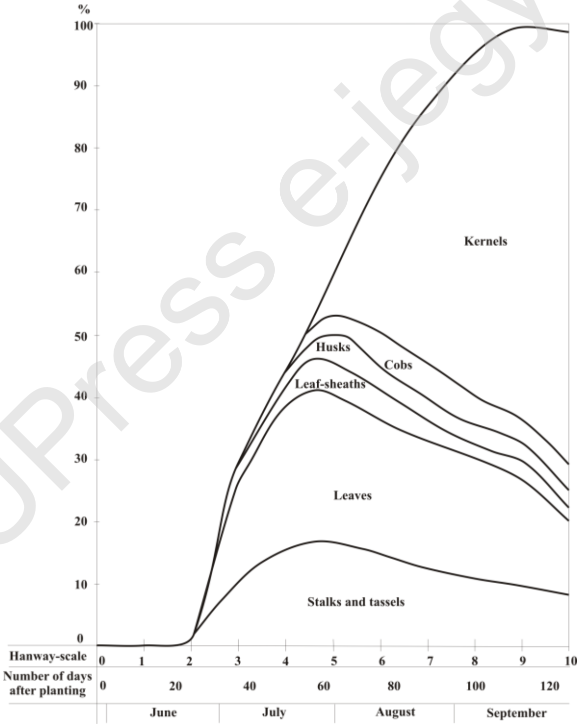

*Figure 2.21* – N uptake of maize. (Source: *Nagy* 2006)

*Phosphorus.* Uptake of this element is very important in the growing plant at the 3–6 leaf stage. At the beginning of the growing season, the dynamic of P uptake is more decisive than the accumulation of dry matter, whereas later, the two processes proceed almost inparallel. In early September, P uptake stops. P uptake is also subject to growing conditions. N deficiency is the most frequent reason for poor P uptake. Lack of N reduces P uptake to 10 kg/ha, lack of K to 29 kg P/ha, whereas P shortage to 23 kg P/ha, as related to a favourable 33 kg P/ha uptake (*Arnon* 1975). Between tasseling and female flowering, 1.2 kg $P_2O_5$/ha/day was recorded. Phosphorus should be available especially during the critical 4–6 leaves stage, subsequently, up to blooming and kernel growth.

Cold weather during the spring hinders the utilisation of P taken up by the plant. Between 12 and 39 °C a rapid P uptake was observed. In the young plant, N-, S-, Ca- and B nutrition were associated with P uptake. Antagonism has been observed between P and Zn. Deficiency of P has similar symptoms to N deficiency. The development of young plants suffers from disturbances as a consequence of ATP-deficiency. Also the mechanism of the stomata becomes defective and water uptake is impaired. The synthesis of pigments is delayed and anthocyanins are accumulated causing a purple discoloration of the leaves. Of the three most important nutrients (N, P, K), P is most represented in the developing kernels (about 80%).

The uptake of P fertilisers is most dependent on the soil conditions. The most available P source is in relatively dry soils for maize the superphosphate. Under unfavourable conditions, phosphorus taken up by the plant may stop somewhere in the stalk and will not reach the kernels (*Figure 2.22*). That type of metabolic problem may be a consequence of deficiency (N) or excess (P) of nutrients, moreover, lack of water.

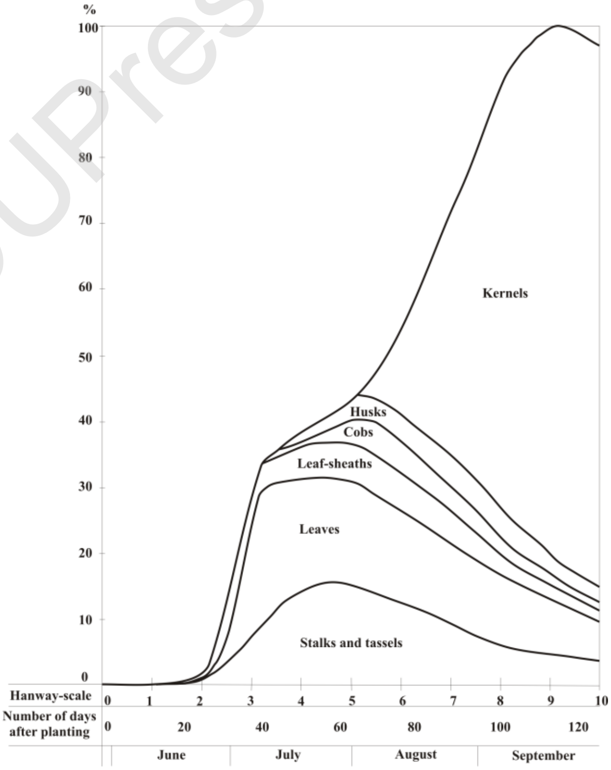

*Figure 2.22* – Phosphorus uptake of maize. (Source: *Nagy* 2006)

*Potassium*. Of the four most important nutrients, the dynamics of K uptake precedes most the accumulation of organic substances in the plant. Around tasseling, K uptake reaches its peak already. Between K and Mg there is an antagonism. The rate of K uptake is 4 kg $K_2O$/ha/day, but may attain 7.3 kg $K_2O$/ha/day (after *Sayre: Arnon* 1975). For a balanced nutrition of maize, an adequate supply of potassium is indispensable.

The utilisation of potassium depends on the original K content of the soil as well as on its availability, the latter being subject to great variation according to the physical properties of the soil. Up to 5% $K_2O$ is the ratio of dry volume in a young maize plant, and it is reduced to less than 0.5% at full maturity. K uptake under N deficiency is 32 kg K/ha, at K deficiency it is 64 kg K/ha, at P deficiency it is 83 kg K/ha, whereas in favourable conditions it is 105 kg K/ha (after *Hanway*: *Arnon* 1975). At the ripening of kernels, the nutrients accumulated in the vegetative parts are rearranged. A major fraction of N and P gets into the kernels, whereas K goes into the stalk and the relative rates of Ca and Mg increase substantially. About one third only of the K content appears in the kernels (*Figure 2.23*).

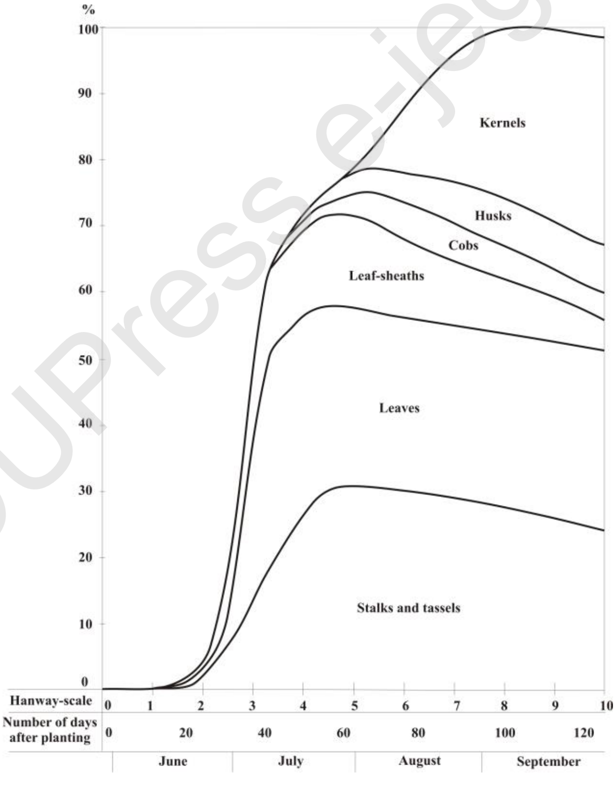

*Figure 2.23* – K uptake of maize. (Source: *Nagy* 2006)

*Calcium and magnesium*. The uptake of Ca is characteristic during the growth of the shoot system and stops around the development of kernels. However, Mg uptake is continuous until maturity. Ca remains in the leaves except for a small fraction (fitin), which goes into the kernels whereas about half of the Mg is found there (*Kreutz et al.* 1977).

The effect of trace elements is less explored in their relationship to maize. Phosphorus is favourable for the uptake of Fe, Cu and Zn into both roots and shoots as well as into kernels. High concentrations of Zn inhibit the uptake of P and its incorporation of the plants, whereas its deficiency impairs the activity of the growth substances. Mn- and Fr deficiency hinders the synthesis of proteins.

### *2.3.5.2. The rearrangement of nutrients in the maize plant during the development of kernels*

Growth substances or phytohormons regulate the translocation of N compounds. With the beginning of flowering, the nutrients accumulated in the vegetative organs of the plant start moving gradually into the developing kernels. The mobility of the individual mineral nutrients is highly variable (e.g. N, P, K and Mg are mobile within the plant, whereas Zn and Ca are less mobile). On the other hand, phosphorus is less mobile in the soil, whereas within the plant, due to the processes in the transporting tissues especially the phloem, its translocation is especially effective. The N content of the vegetative organs – from the lower years and the stalk – 60–65% is getting to the kernels. Firstly the N content of the tassels declines, followed by that of the stalk and of the leaf sheaths and subsequently of the leaf blades. About 40% of the nitrogen in the kernels is supplied directly by the roots. In the N-supply of kernels, individual organs are shared at different rates; leaves participate by 58–60%, husks by 11–12% and the stalk by 19–26%. The flux of phosphorus follows later and depends strongly on N supply. About 23% of the K content of shoots is translocated into the kernels from different organs except stalks. In the stalk, K content often increases during the ripening process. Some 70% of Mg taken up comes from the leaves into the kernels, and 20% only from the stalk.

### *2.3.5.3. The role of nutrition in the development of maize*

Deficiency as well as excess of nutrients impair the growth and development of plants and are manifested in morphological anomalities and in reduced quantity as well as quality of the yield. Symptoms of deficiencies have been studied in different countries for many years. Visual signs are highly useful in recognising the real causes of deficiencies. However with the appearance of acute symptoms, the hope to correct the deficiency instantly is often vain. Therefore, it is important to recognise the deficiency as early as possible in order to achieve a successful intervention. The movement of nutrient in the soil and the uptake of them by the roots are widely variable. In sandy soils, the compounds of fertilisers are much more mobile than in loam and clay soils. Therefore in light soils, the nutrients tend to be exhausted quickly and deficiency symptoms appear earlier than in heavy soils. In heavy soils, supplies of nutrients last longer and the colloid content is able to absorb the excessive concentrations of salts thus protecting the roots, whereas in sandy soils toxic effect may appear especially under conditions of drought. Nutrient supply of the soil can be assessed either by soil- as well as by plant (leaf) analysis (*Bergmann* & *Neubert* 1976). On the basis of the chemical composition of crops examined, it was stated that the seasonal effect is often much more important than that of the fertilisation. Therefore, it is not adequate to determine the limiting doses of fertilisers on yields (they are needed rather for the purpose to repair the substances lost by the crop). The examinations of different plant organs (leaves, stalk, root, whole plant) called the attention of the researchers to special regularities. It turned out that leaf analysis does not inform adequately about nutrition, therefore occasionally an analysis of stalk; leaves sheaths or the whole plants can be more informative. Therefore the expression of plant analysis is more adequate than leaf analysis. The time of sampling is also a decisive point of a successful check. In a young plant the nutrients taken up prevail, whereas later the minerals are mostly incorporated into organic compounds, and their dilution.

The correct recognition of the nutritional status facilitates the planning of measures to complete the supply of nutrients to the growing crop (by top dressing or leaf dressing) including also the demands of the subsequent crop planned for the same site. The function of growth and yield expected based upon the supply of nutrients is not linear. It is a proven fact that yields could be increased initially by the available nutrients (by fertilisation and irrigation). However, with the increasing production of organic dry matter, the concentration of nutrients declines as a rule. With further doses of nutrients beyond a certain optimum, the concentration of nutrient in the soil will increase and the excesses of concentration will manifest themselves in physiological disorders, and the nutrient level measured within the plant declines again. Smith compared this relationship in 1962 (*Wallace* 1966) with a returning curve. A content of nutrient necessary for maximal yields depends also on the level of yield. Excessive doses may impair the yield because of their toxicity. The mutual relationship between the nutrient content of soil and plant has been pointed out by *Mengel* & *Kirkby* (1979).

### *2.3.5.4. The role of the most important nutrients in the metabolism of maize plants*

*Nitrogen.* This element is an important part of living organisms as an essential constituent of protein as complicated constructions of amino acids, carrier of living processes, the material basis of genetic information and cellular functions. In the soil, N occurs in two forms, either as $NO_3^-$N or as $NH_4^-$N. Roots are also able to take up organic N compounds, e.g. urea (carbamid) and amino acids; the uptake may ensue also through the leaves. Generally, the roots utilise the nitrates and the ammonium compounds. The physiological effects of the two latter compounds are different. With the uptake of $NO_3^-$N the pH value increases, whereas with the uptake of $NH_4^-$N the pH declines. At pH 6.8 the uptake of the two forms is nearly equal. Plants take up from acid soil mainly $NO_3^-$N. Referring to maize, the uptake of $NO_3^-$N is preferred in the provision of nitrogen. This form influences also the relationship between anions and cations within the plant. The presence of nitrate as an anion stimulates the uptake of cations, whereas ammonium, as a cation, hinders the uptake. All N fertilisers incorporated into the soil are sooner or later transformed into $NO_3^-$N by the activity of microorganisms.

*Phosphorus.* P is also an important constituent of the living cell. In compounds involved in the metabolism and other processes of living cells requiring energy, P is indispensable. The manifestation of the genetic information as well as photosynthesis is dependent on ADP and ATP. Transformation of solar energy into chemical energy in a host of organic compounds is the common phenomenon in plants. Uptake of P ensues in forms of $H_2PO_4^-$ and $HPO_4^{2-}$ as ions of negative charge from the soil after the orthophosphate salts are diluted in water. The dominant ion form in the soil depends on the reaction. In acid soils, the univalent water-soluble prevails, whereas in basic soils the bivalent, less soluble form is dominant. P fertilisers tend to be bound chemically in the soil depending on the pH reaction of the soil. For that reason, the movement of P-fertilisers is slow and therefore their utilisation has very limited opportinities.

*Potassium.* It is an element, which does not participate in the structure of the living organism, but its presence as an ion is needed in the living cells. Together with its antagonist calcium, potassium regulates the permeability of cell membranes, which means the water husbandry of the living cell. By activating many enzymes, the role of K is outstanding in the metabolism of plants. The regulation of functions of stomata is involved in the resistance or tolerance to diseases, moreover, in the stability of stalks.

*Calcium.* It appears as a cation in salts of organic and inorganic acids diluted or precipitated in plant cells. The stability of cell walls, the regulation of water penetration and the stretching of cell walls and the differentiation is associated with the functions of calcium. In growing roots, calcium is indispensable. In dicotyledonous plants as well as in other plants, which synthesise more organic acids, calcium is an important requisite.

*Magnesium.* It is an indispensable constituent of chlorophyll and consequently for photosynthesis. In several cases, Mg participates also in the processes of phosphorylation as activating enzymes.

*Trace elements* (Mn, Mo). In the protein synthesis of maize, the enzyme nitrate-reductase is regulated by those trace elements. Some enzymes are activated equally by $Mg^{2+}$, $Mn^{2+}$ and $Zn^{2+}$. $Zn^{2+}$ catalyses the binding of NADP (nicotinamide adenine dinucleotide phosphate) and of NAD (nicotinamide adenine dinucleotide) to the carrying proteins. It promotes the formation of the amino acid, tryptophan. Tryptophan is known as the precursor of indole-acetic acids, an important group of growth substances which are decomposed at higher temperature, consequently the plant needs Zn to restore this phytohormone. There are still gaps in the interpretation of the role of trace elements. Maize is less susceptible to deficits in other trace elements, or even indifferent, therefore their role is still unexplored. If some of the above mentioned elements, e.g. K, Mg, Mn, Mo and B are involved in functions like activation or inhibition of enzymes, problems will be observed in the metabolism or energy flow, which will express itself, sooner or later, in the performance of the crop.

An excess of nutrients manifests itself by symptoms as a consequence of overdosing of fertilisers, e.g. P and K, or low pH values, antagonism of metal ions causing deficiency symptoms (e.g. K – N, Mg – Mn, etc.) in sandy soils may occur as an effect of overdosing fertilisers. Excessive N may induce luxurious growth and prolongation of the growing period and burning on the leaves. Excessive phosphorus disturbs the utilisation of Fe (iron) and especially of Zn; moreover, deficiency of Ca, B, Cu and Mn may also appear. Excessive potassium may cause Mg and Ca deficiency and inhibition of uptake of B, Zn, Mg and $NH_4$. Too much calcium, which may occur less frequently (in soils on limestone or as a consequence of liming), impairs the uptake of trace elements and of P. Deficiency of any of the elements may jeopardise the normal metabolism of the plant as a consequence of the relative overdosing of other elements because the balance between the elements is disturbed. That type of problem could be assessed by plant analysis and the results provide valuable information. According to *Dennis* (*Bergmann* 1979) the ratios of nutritive elements considered to be normal at flowering time are the following: N:Zn=1000, P:Zn=100, Ca:B=300, Fe:Mn=2, S:Zn=80, S:Mn=30, K:Mn=400, Fe:Cu=12.5, Fe:Cu+Zn=3.5. *Bergmann* (1979) claims that if the P:Zn ratio >300, Zn deficiency arises in maize, between

300 and 201, a hidden deficiency is expected, between 200 and 50, it is sufficient, above 25, Zn is in excess.

#### *2.3.5.5. Deficiency symptoms*

Deficiency symptoms appear as soon as some of the important nutrients and trace elements are not supplied at an adequate level. Nitrogen and sulphur are needed for amino acids, phosphorus for nucleotids and metabolism, magnesium for chlorophyll, calcium for pectins, iron, copper and zinc for the activity of enzymes. *N-deficiency:* older leaves start yellowing then drying beginning at the tip and along the ribs. *P-deficiency:* older leaves and subsequently the stalks become a purplish colour, whereas the rest of leaves turn dark green. *K-deficiency:* the internodes of the stem are excessively short, the stem remains thin, leaves are though long, but start yellowing in stripes at the tip and along the margin. *Ca-deficiency:* developing leaves tend to stick to each other when protruding from the sheaths. *Mg-deficiency:* local accumulation of chlorophyll appearing as green stripes as a kind mosaic pattern (tiger stripes). *Zn-deficiency:* maize is very susceptible to it. Older leaves at the base on both sides along the midrib as a 2–3 cm wide stripe start to become pale or almost white. Young leaves emerge pale yellow or white. Problems are experienced also in the fertilisation of ears.

### *2.3.6. Water management of maize plants*

Maize plantations utilise considerable amounts of water during the growing season. The water is taken up and transpired into the atmosphere of the environment. Taking the volume of the plant, the water going through the roots and leaves is a multiple of it, and only a small fraction is withheld by the plant at full maturity, therefore, for calculating the water management of the plant it could be ignored. Maize is considered according to its water consumption as an average or moderately water requiring crop. In Hungary, water supply is the most decisive ecological condition of successful maize cultivation, being the most important factor of yield. That is because soils of a favourable water management and water storing capacity are recommended for its production. The natural precipitation is the main source of water, although its extreme spatial and seasonal variability is a serious handicap. Maize is often exposed to extreme stresses either by drought or by excess water. One of the key principles of maize production is a tillage system that conserves the most water because the precipitation during the growing period meets hardly the water requirement of maize on the majority of growing sites.

For the purpose of analysing the water requirement of maize, we should start with an assessment of the temporal and spatial distribution of water reserves in the soil. The data of annual precipitation is basic information, but we should not forget that water supply and precipitation are not closely correlated, although there is a high probability between them. The infiltration and subsequent conservation of water depend largely on the physical properties of the soil. While in sand and in light soils, some 300–350 mm/m water is stored, in loam soils considered to be optimal for maize 350–450 mm is retained, whereas in heavy clay even much more than that. A fraction of those values is available for the plants. Obviously, extremely light and heavy soils, sands and clays, do not meet the demands of maize mainly because of their insufficient content of available water. In sand, water is lost through gravity as it cannot be retained by the low values of the colloid fraction. In clay soils, the water is bound by the high fraction of colloids (>50%) with energy higher than –15 atmospheres. Water management of the plant in the root zone of the soil does not modify the physical regularities, which dominate throughout the growing season.

### *2.3.6.1. Water requirement, water consumption, water supply*

*Water requirement* is an important physiological term; it represents the water quantity which secures sufficient moisture continuously for the tissues of plants, mainly in the leaves, under various air temperatures and humidity. This value expresses the water potential of the plant, which varies between 0.0 and –5.0 atmospheres and corresponds with water content of leaves higher than 75%. As environmental factors may change substantially between wide limits, the optimum moisture content of the soil in the field is variable. Between the lowest and highest values of that interval the moisture content may meet perfectly the water requirement of the plant. When the moisture content does not reach the lower limit of that interval, water deficiency occurrs, whereas above the maximum values of the interval, there is a water surplus. As a consequence of variation in the moisture content of soil, both unfavourable insufficiencies as well as excesses of water may ensue in the plants. Water insufficiency starts with the condition when water uptake from the soil stops because the water binding energy of the soils exceeds 15 atmospheres, i.e. the sucking energy of the plant root. Deleterious water excess also hinders or stops the water uptake of roots but in that case by the lack of air. Most damage caused by lack or excess of water is lethal. But it is not normally the lack or excessive amount of water, which is lethal to the plant but rather the time span of that type of extreme condition. The interrelation of those concepts is expressed in *Figure 4.24*, which showes that variation of moisture content of the soil may induce very different conditions and risks in the plant._

| scarity of water | | | | excess of water | | |
|---|---|---|---|---|---|---|
| | | | optimal supply | | | |
| *lethal drought* | *deleterious scarity* | *initial scarity* | | *initial surplus* | *deleterious surplus* | *lethal excess* |

*Figure 2.24* – The interpretation of the concepts: water requirement, water consumption and water supply.

(Source: *Szász* & *Nagy* 2006)

In Hungary, extreme cases of water management may occur with different conditions and duration. In the western part of the country, the excess of moisture may occur during springtime, then in early summer as inland water. Forest soils with an unfavourable water management become water-saturated by the melting snow, plus occasional precipitation which may feed prolonged presence of inland waters. If excessive water is accumulated in the upper layer of the soil, it is still tolerated by the plants. In central and eastern regions, the loam soils used to be saturated up to about 85% of their water capacity by hibernal (winter) precipitation, thus the vernal (spring) rains could find spare capacity; meanwhile evaporation may counteract the occasional excesses of water. Sandy and argillaceous soild are on the other hand less recommended for maize because of their unfavourable water management.

On the Great Plain, drought periods frequently affect the crops especially in the second part of the summer as soon as the water reserves tend to be exhausted and precipitation is lacking. During drought, the only source of moisture is the water reserve, which is bound to the soil by 8–12 atmospheres sucking energy. The lack of moisture is especially deleterious on clay sites, where the reserves may be abundant but as the only source of water their movement is jeopardised. The layers near to the roots become dry and further away the moisture seeps too slowly because the hydraulic stress. That special type of drought occurs frequently in the upper layers of the root zone.

The excessive episodes of water management affect immediately the life processes of maize, therefore the efforts of the grower are aimed ar preventing and averting the consequences and *securing a harmonious water supply by facilitating a continuous water management*. That is the main task of the tillage system to be chosen.

*Water requirement is a genetically coded property, which is modified by the actually existing ecological conditions.* One of its characters is the variability experienced during the growing season, as being generally low during the first part of development, then increasing during the period of rapid growth and flowering, then declines gradually towards the end of formation and filling of the kernels. Depending on the atmospheric conditions, the water requirement of the plants varies from day to day. With increasing temperature, evaporation increases in parallel with other life processes, which is called *thermoregulation.* As the relative humidity of the air declines, the water uptake of the plant is stimulated as an effect of *hydroregulation.*

The interrelation of the water requirement of plants and of moisture content of soil is a very important practical question. The water requirement of plants is expressed by the *static water requirement.* This specifies the optimum water-air relationship in the soil for the plant. The optimum static water requirement depends on the physical type of soil, i.e. its composition of different size of granules. The optimal rate is found in loam soils of medium heaviness and of 60–85 volume density %, storing water up to 15–40% of their volume. The numerical expression of the total and the available water content may characterise the relevant properties of the soil. As water requirement increases during the growing period up to flowering, therefore it is important to consider the water amount per time and per area. That value is known as *dynamic water requirement* (mm/hour, g/m$^2$/hour, mm/day, etc.).

The temporary variation of *water supply of maize* depends on precipitation and the properties of water management of the soil. Precipitation is as a rhythmic climatic parameter characterised by averages computed from data of many years: after a winter minimum, increasing monthly doses peak in May in western Hungary and in June east from Lake Balaton. This one-phase sequence of precipitation is typical for the continental climate. However, precipitation is variable to such an extent that data of single years do rarely comply with this rule. The patterns of other climatic types are also recognised in some years: oceanic if the maximum is shifted to the mid of summer, Mediterranean if maxima are in the winter and minima in the summer. Dominant continental effects are recognised by low precipitation both in winter as well as in summer. The three different types of climates appear as an unstable combination among them. That is the cause of the capricious annual variation which makes maize cultivation as a water dependent culture risky and threatened by natural adversities in most seasons.

If one compares the water supply with water requirements, the mis-match can be either positive or as negative. The experience of many years is that the positive risk, or excessive water, is more unusual whereas the negative, or lack of precipitation, is more frequent. The value considered as decisive in those assessments is based on parameters representing the *water requirement of plants,* but the risk is much higher than the annual means of many years would indicate for almost the whole area of the country. The value indicating the water supply of maize is relative because it depends on the water requirement and cannot be assessed on the basis of annual or seasonal means of precipitation alone, the spatial variation of water requirement ought to be considered as well.

*Water consumption of plants is only one constituent of the formula which expresses the extent of evaporation. It indicates the amount of water released by the plant into the atmosphere during a unit of time.* From the practical point of view it is a parameter, which expresses the best water supply and the potential values of the agrohydrological situation. The water lost by the plant to the atmosphere is the *evapotranspiration*, which has two components: the evaporation from the soil as well as the transpiration referred to one unit area (mm, g/m$^2$). The energy required for evaporation of water is 2430 kJ/kg, the same referred to precipitation is 243 J/mm/cm$^2$. The expression of water released from the soil is called *evaporation,* whereas through the leaves water is *transpiration.* We have to consider transpiration as a physical process, which is modified by biological and agrotechnical means.

### *2.3.6.2. The potential water consumption of maize*

The concept of evapotranspiration (ET) is the sum of evaporation from the soil and from the leaves of the plant. Evapotranspiration depends on several factors; it is a value of a function. This function is limited in a physical sense because both limits, minimum and maximum values, are determined by the supply of energy. If the solar energy is zero, the intensity of evapotransiration is also zero, and maximum values are also bound to the maximum energy supply. The maximum of evapotranspiration is the so-called *potential evapotranspiration* ($ET_0$), which expresses the amount of water evaporated according to the physical conditions of the atmosphere as long as water is not lacking. That means e.g. a leaf may transpire as long as it is saturated up to its minimal water capacity or the leaf with maximal water content will transpire exhausting the potential of evaporation. Whenever the water supply does not attain this level, the value will be reduced due to greater or lesser want of water, therefore the *effective evapotranspiration* will be lower than the potential level. The practically used values of the potential and the effective evapotranspiration are expressed by the sum of mm/day, mm/5 day, or mm/month. Evaporation is an energy-consuming process; therefore it is possible to approach it from the point of view of energy consumption.

The factors determining potential evaporation are those below:

– the net energy of solar radiation arriving to the spot (balance of radiation): $R_n$ MJ/m$^2$

– the relative air humidity (%)

– the movement of air as wind velocity in units: m s$^{-1}$

The measurement of potential evapotranspiration could be performed with several methods which shall not be introduced here with the remark that most of them are empirical formulae, but the computing developed in Hungary proved to be satisfactory with useful results (*Szász* 1962, 1973a, *Antal* 1968, 1972, 1998, *Varga-Haszonits* 1977). In spite of that, potential evapotranspiration, being an estimated value its utility, is exploited by calculating the daily water utilisation which could be evaporated maximally. It gives a reliable basis for comparison.

The potential evapotranspiration is of course a plant-specific value; it is influenced by the ratio of the soil and the leaf area. While the potential climatic evapotranspiration is referred usually to a short lawn, it is not acceptable in relation of plant populations with large leaf area. Knowing the leaf area index (LAI), the potential evaporation could be calculated for different plant species taking the climatic potential evaporation as a basis (*Posza* & *Stollár* 1983, *Szász* 1968, 1973b, 1984). The values of the potential evapotranspiration and the optimal water requirement are close to each other, as $\Sigma PE_0 > \Sigma W_n$ ($W_n$ is the sum of the optimal water requirement during the growing season). In the case of maize, the optimal water requirement amounts to 85–90 % of the potential evapotranspiration. *Figure 2.25* shows the spatial distribution of the potential evapotranspiration. From the mean values of the regions, we may recognise the areas where the risk of drought is high and where the precipitation is abundant in the western part of Cisdanubia.

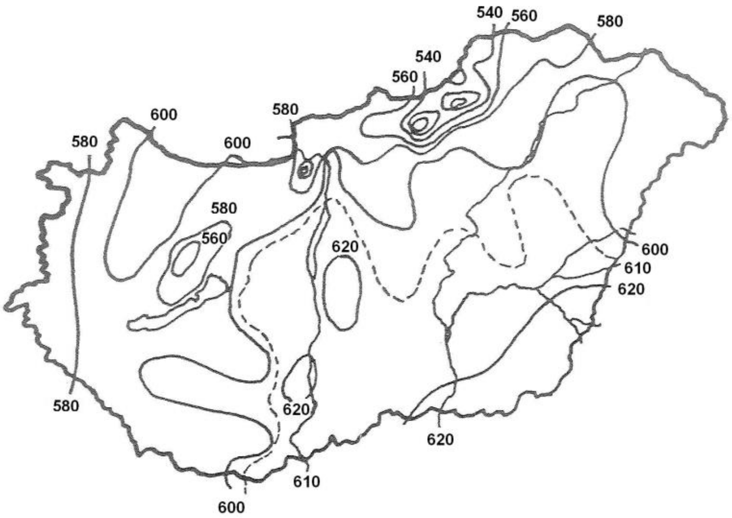

*Figure 2.25* – The potential evapotranspiration in Hungary (April-September). (Source: *Szász* 1963)

During the summer, values of potential evapotranspiration are evenly distributed over the whole Great Plain region. As a mean, the annual 600 mm of the Great Plain changes to less than 600 mm in the western strip of the country only. That mean value indicates that the water requirement of maize exceeds the evapotranspiration, optimal water requirement and the amount of precipitation. *Figure 2.26* shows the spatial distribution of the optimal water requirement of maize within an interval of 320–480 mm. We may state that in the important maize growing region – South-Hungary – the highest values of evapotranspiration are registered, which means that there is the highest frequency and risk of drought.

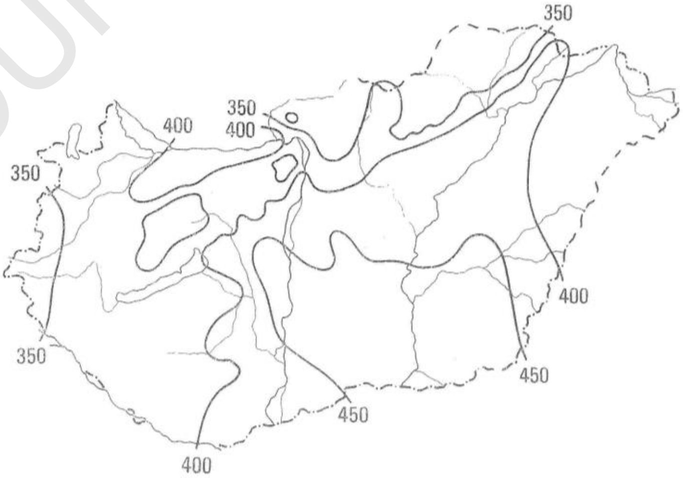

*Figure 2.26* – The spatial distribution of the mean water requirement of maize during the growing season.

(Source: *Szász* 1988)

It is worthwhile to compare the potential evapotranspiration, the optimal evapotranspiration, the optimal water requirement and the annual precipitation as means of many years. It is a useful aid to look at *Figure 2.27* presenting the spatial distribution of the annual means of precipitation. Clearly, there is a substantial difference between the precipitation and the water requirement of maize. In the maize growing areas, water requirement during the growing season exceeds the average level of precipitation by some 100–150 mm, in some localities even by 200 mm. In the southwestern part of Cisdanubia, the lack of water is somewhat less than elsewhere, but still exists. The general conclusion is justified that *in Hungary, maize is grown as a rule under conditions of moisture shortage*. The deficiency varies between 0 and 200 mm per growing season, especially in the central and southern region of the Great Plain and in the Hajduság, most frequently reaching deleterious levels. In SW-Cisdanubia it is less threatening with an average deficiency of 40–80 mm.

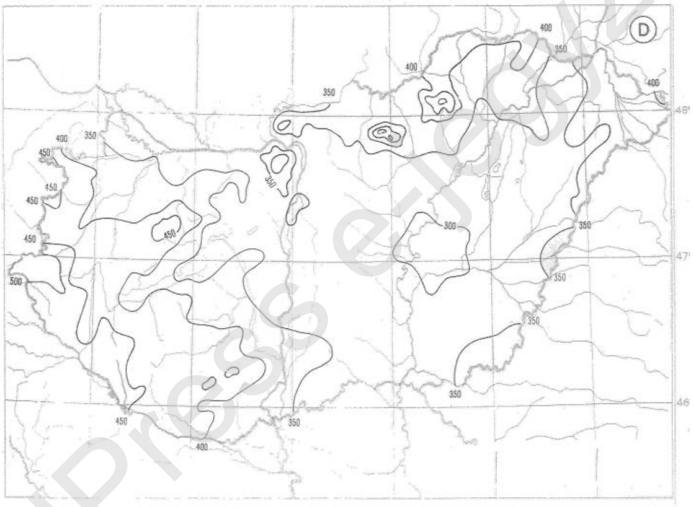

*Figure 2.27* – Spatial distribution of precipitation during the growing season in Hungary (April-September).

(Source: *Szász* & *Nagy* 2006)

The variation in the *dynamic water requirement of maize* during the growing season demonstrates the measure of the water requirement. For orientation, we may survey the daily dynamics of water requirement. The dynamics during the growing season can be interpreted by several methods. On the one hand, the monthly changes of the optimal water requirement may followed, on the other hand, the curves representing the accumulated water requirement could be visualised. *Figure 2.28* shows changes in the monthly as well as in the accumulated water requirement of maize.

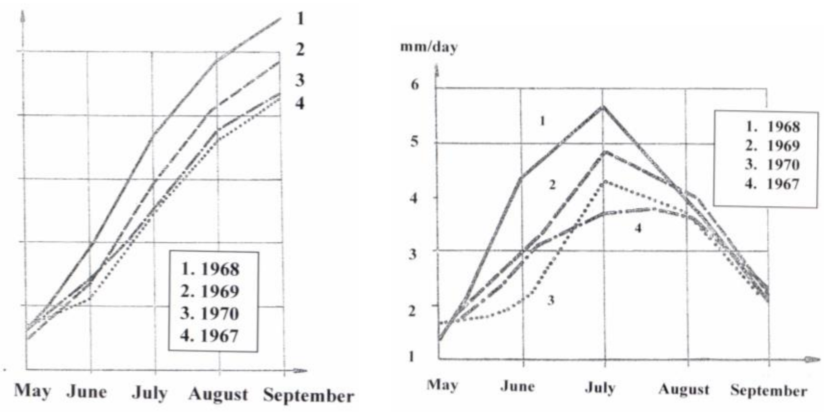

*Figure 2.28* – The accumulated as well as dynamic distribution of water requirement of maize plantations.

(Source: *Research Institute of Irrigation,* Szarvas 1971)

On the right side of the figure, mean values of four-year averages of the monthly water requirement are visible. It is evident that in May the daily water consumption is still very low, but in June it could vary substantially (2–4 mm/day) depending on the size of plants as well as on the weather. The highest values of water consumption occur in July after the beginning of flowering attaining 3.5–5.5 mm/day depending on weather conditions. With the end of flowering water consumption declines gradually, and its variation is moderate. In August the daily rate is 3.5–4.5 mm/day. In September, the uptake of water is reduced and the measured values of evapotranspiration include the water loss from the senescent plant tissues, and vary around 2.0–2.5 mm/day. The same dynamics are also recognised in maize plantations of different planting dates, in hybrids of FAO number 400 or more, which may still show high water consumption in September.

The *accumulated water consumption of maize* is shown on the left side of Figure 2.28. It is like a curve representing growth of the plant. At the beginning and at the end of the growing period the slope of the curve is rather modest or moderate, whereas in the middle of summer until the middle of July the curve is the steepest.

The *daily rate of water consumption* is analogous to the daily rhythm of other cultivated plants, but the volume consumed per hour may differ significantly. Depending on the respective phase of development, the maximum occurs at noon and may attain 1.5 mm/hour as a potential maximum. The effective value of evapotranspiration is lower than that, but may exceed 1.0 mm. The daily process of evapotranspiration is not symmetrical, the morning consumption is more important than the afternoon consumption.

The potential evapotranspiration is determined by several main factors. Before dealing with those factors, we should firstly describe the potential water consumption of maize in Hungary and its temporary distribution. The data in *Table 2.3* refer to the Central Great Plain, which is rather representative for the whole country, and knowing the local values of radiation, temperature and precipitation we may also estimate conditions of other parts the country.

*Table 2.3* – The potential water consumption ($\mathrm{PET}_K$) of maize in the Central Great Plain

| Month | IV. | V. | VI. | VII. | VIII. | IX. | Total | |
|---|---|---|---|---|---|---|---|---|
| 1. $\mathrm{PET}_0$ | 2.47 | 3.19 | 3.67 | 3.94 | 3.81 | 1.96 | | mm/day |
| 2. $\mathrm{PET}_0$ | 74.58 | 99 | 110 | 122 | 118 | 61 | 584.58 | mm/month |
| 3. $R_n$ (radiation balance) | 3.34 | 4.26 | 4.49 | 4.89 | 3.24 | 2.23 | | mm/day |
| 4. $\mathrm{PET}_0/R_n$ | 0.74 | 0.75 | 0.82 | 0.81 | 0.85 | 0.88 | | |
| 5. K | 0.02 – 0.04 | 0.04 – 0.08 | 0.18 – 0.44 | 0.81 – 0.97 | 0.81 – 0.57 | 0.30 – 0.04 | | |
| 6. $\mathrm{PET}_K = K \cdot \mathrm{PET}_0$ | 0.05 – 0.09 | 0.12 – 0.25 | 0.67 – 1.61 | 3.19 – 3.82 | 2.62 – 2.17 | 0.59 – 0.08 | | mm/day |
| 7. $\mathrm{PET}_K = K \cdot \mathrm{PET}_0$ | 1.50 – 2.30 | 3.96 – 7.92 | 19.8 – 44.4 | 98.8 – 118.3 | 100.4 – 81.2 | 17.7 – 2.5 | 242.16<br>256.62 | mm/month |
| 8. Transpiration | 2 | 12 | 40 | 109 | 93 | 11 | 267 | mm/month |
| 9. Evaporation of soil | 73 | 87 | 70 | 13 | 25 | 50 | 318 | mm/month |

Source: *Szász* & *Nagy* 2006

Explanation of the abbreviations in the Table: $\mathrm{PET}_0$: climatic potential evapotranspiration; $R_n$: water equivalent of the radiation balance (mm); $\mathrm{PET}_0/R_n$: the quotient of the daily climatic potential evapotranspiration and of the radiation balance; K: the factor of the plant expressing the interval of values in the different months; $\mathrm{PET}_K$: the potential evapotranspiration of the maize.

The determination of potential water consumption of the plant ($\mathrm{PET}_K$) is performed partly by measurement, partly by calculation. The first two rows of the Table contain the data of the so-called climatic potential evapotranspiration, which are considered to be valid for the given surface of reference. That surface of reference is a lawn, where water from the soil underneath would evaporate at minimal water saturation like a water surface, which is a possible climatic maximum. This value is during the six months of maize culture about 585 mm. The monthly sums may vary greatly, of course, and the maximum ensues in July, which is in the Central Great Plain about 120 mm. In the south this value is higher (120–140 mm) and in Cisdanubia less than 120 mm. In the first row of the Table, the daily means are shown. Those values do not appear directly but are valid, all the same, in the sense that water consumption of maize cannot exceed these values for physical reasons. It should be emphasised that the averages may be greater on warm, dry days approaching even 6 mm/day. Similarly, the mean values of other months, where the upper limits of the value of evaporation are much higher. The maximum of evaporation being still possible for energetic reasons are found in the 3rd row of the Table, whereas the variation may ensue as 3.34–4.9 mm/day because the energy needed is provided by solar radiation. The 4th row of the Table shows the values of the so-called relative evapotranspiration, which is the quotient of the potential evapotranspiration and the radiation-balance. The energetically possible evaporation cannot be achieved because it is inhibited partly for thermal reasons and partly by vapour saturation of the atmosphere. It is generally true for Hungary that the potential evapotranspiration cannot exceed 70–90% for energetic reasons.

The structure, water requirement and development of the plant population modify significantly the values of the potential water consumption. For the purpose of estimation, the introduction of the „K” factor as specific for the plant expressing its relationship to the evaporating water surface. This value is always less than unity, very low at the beginning, and increases with the growth of plants approaching 1. The factor “K” characterises the dynamic of transpiration. In row 5, the minimum and the maximum values are indicated. The monthly change in K is considerable. The potential evapotranspiration of maize is indicated in the 6th row as changing monthly. In every month, the maximum and minimum values are calculated as upper and lower limits, which may be understood as differences between the beginning and the end of the respective month. Once the daily values are known, the monthly potential water consumption can be calculated, which is shown in the 7th row of the Table. The relatively low values at both positions, lower and upper, which means that they are averages and therefore actual measurements, may differ substantially from those indicated. *Petrasovits* & *Balogh* (1969, 1974), *Antal et al.* (1975), and *Ruzsányi* & *Szász* (1983) observed that extreme heat and dry seasons may produce conditions of more than 500 mm potential water consumption; therefore the maximum values in the 7th row refer to transpiaration only. The high values are a sum of transpiration plus evaporation from the soil, which is expressed in the 9th row, thus 267 + 318 mm = 585 mm as evapotranspiration, a real approach to the real world. Under natural conditions of evapotranspiration the upper values may be reached if plenty of water is given, although then runoff may also ensue.

Summing up the characteristic numerical values, we should state that maize is a water requiring plant, which becomes really critical around flowering, when the precipitation tends to be insufficient. At that time the evaporation from the soil is only a fraction (12%) of evapotranspiration, and 88% of water passes through the plant as transpiration. During this period, the development of stress as a consequence of water deficit is an obligate phenomenon in maize production. This stress is a decisive cause of the modified evapotranspiration

### *2.3.6.3. The numerical characterisation of the actual water consumption of maize*

The potential daily water consumption of maize is very variable during the growing season, but the real variability of it is essentially higher than that. While the potential water consumption depends on the climatic conditions almost exclusively, *the true evapotranspiration* (TET) is derived from the potential evapotranspiration (PET) and as the most important factor of the water balance, i.e. *water content of soil*. The daily value of the real evapotranspiration may vary within the interval of 0 – PET mm/day. The true daily water consumption cannot attain the potential value with a few exceptions; therefore its accumulated value is always lower than the potential evapotranspiration. *The difference between potential and true water consumption expresses the water deficit, whereas the quotient of true per potential water consumption is the value of the relative water consumption.* By means of those two values, the water management of the maize plantation is duly characterised. The higher the daily water deficit, or the relative water loss, the lower is the moisture content of the soil. This statement indicates that the above-mentioned parameters facilitate the numerical description of the water management of the crop, as far the hydrophysical properties of the soil are known. Taking into account the climatic conditions of the countryside and the hydro-physical properties of the soil, the moisture content of the soil would be sufficient to calculate the real water consumption of the crop.

The water consumption of a maize plantation, which means the value of true evapotranspiration are valuable theoretical and practical information. During crop production, the temporary variation of the true evapotranspiration expresses the ecological (environmental) status of the growing site from the point of view of maize production. Therefore this knowledge is considered to be indispensable.

The maize field is a complex agro-ecological system, which is composed of two subsystems: the soil and the crop plants. The two subsystems are in a close interaction with each other. Both are heterogeneous in their composition where, in different layers, special living organisms are found which is all subject to complex climatic effects expressed through temporary and spatial changes. Subsequently, the regularities and causal relations of real evapotranspiration will be dealt with.

There are a couple of factors, which are decisive in forming the values of evapotranspiration but it is first of all the radiation, which deserves attention. *Distribution of radiating energy in the plant population depends mainly on the structure of the plants*. During the development of the plants, the density of foliage and the orientation of leaf blades change continuously, therefore the absorption of energy is variable in the same layers. As a consequence, the energy maintaining the process of transpiration appears at various extents in the successive layers. In a young population during the first part of development, foliage density is permeable for about more than one half of the vertical penetration of energy. With the increasing density and the leaf area index (LAI), the structure grows more heterogeneous. The upper one third of plant structure, where the leaf density is low, the second third represents the highest foliage density, then the lower third of the canopy is again less dense, and the absorption is moderate.

The penetration of the global radiation across the plant canopy and its absorption is shown on the left hand side of *Figure 2.29*. Values of the energy absorbed express the amount of transpiration referred to the leaf blade area as far as other properties of the plant stand are explored. On the right hand side of the Figure, the intensity of transpiration is introduced, and may be traced along the profile.

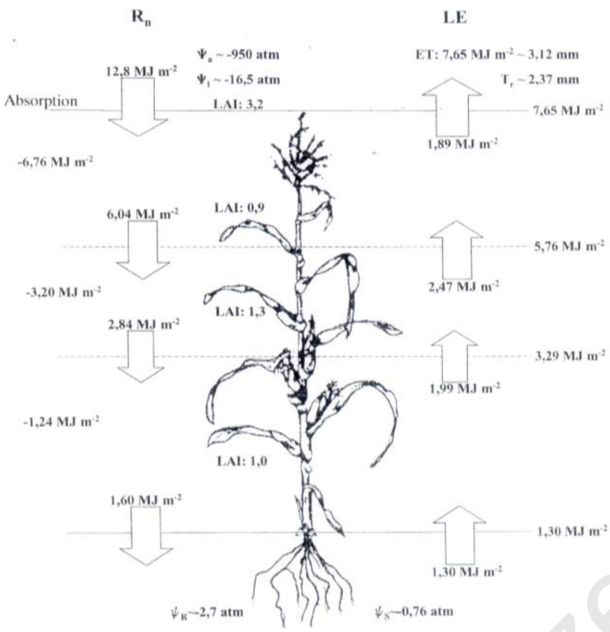

*Figure 4.29* – The energy and water balance of a maize population at the time of flowering.

(Source: *Szász* & *Nagy* 2006)

($R_n$: balance of radiation. $ET_a$: real evapotranspiration. $T_r$: transpiration.

LAI: the leaf area index of the respective zone. r: resistances. $\Psi$: water potential)

According to examinations, the most intense water loss is recognised in the central region where the density of foliage is highest and the most energy is absorbed. The water circulation is moderate in the upper zone and it represents the second level. The less intense transpiration is experienced in the lower zone of the canopy. Less energy is paralleled by modest transpiration; moreover, high air humidity, moderate temperature and low wind speed impair the intensity of transpiration. The spatial distribution of transpiration intensities is generalised, in spite of that, there are other processes, which may also influence transpiration. The basic phenomenon is recognised throughout the whole day and at all phases of plant development.

The rate of absorption of the incident energy, or the rate of the energy, which is utilised to maintain transpiration, is an important question. Detailed information has been gained from field experiments and extended calculations. To answer the question, what is understood under evapotranspiration measured above a plant population, we should state that evapotraspiration is the sum of transpiration through the leaves and the evaporation of the soil surface. From the point of view of practical plant production, the ratio of transpiration and evaporation is an important parameter. In a young crop, the evaporation of the open soil surface is dominant, gradually, that ratio approaches unity when the LAI of the crop is 1.0–1.5. With the increasing LAI, transpiration increases and exceeds many times the evaporation from the soil. The fully developed plants absorb the 80% of the energy and leave 20% to stimulate the evaporation of the soil. The increasing density of the plant population may improve the above ratio. The interaction of LAI, penetration and absorption is demonstrated in *Table 2.4*.

According to the above ratios, the role of the components and the utilisation of solar energy may provide a general impression concerning the exploitation of natural resources by agrotechnical means.

*Table 2.4* – The relative values of LAI, light penetration and absorption in maize populations

| LAI | Penetration | Absorption |
|---|---|---|
| 0.1 | 94 | 6 |
| 0.5 | 74 | 26 |
| 1.0 | 54 | 46 |
| 1.5 | 40 | 60 |
| 2.0 | 30 | 70 |
| 3.0 | 16 | 84 |

Source: *Szász* & *Nagy* 2006

The relationship between exploitation of energy and transpiration is rather close. However, *the temperature measured within the plant canopy* strongly influences the intensity of photosynthesis. In general, in the centre, the middle zone of the maize population, the temperature is higher with 1.0–2.5 °C than in the surrounding space depending also on the wind speed. The higher temperature is a function of the moisture content of the soil. In the case when the moisture content of soil is lower than 50% in the root zone, the transpiration declines, but as the transpiration does not absorb the energy, the latter is used to warm up the environment. By this way, transpiration is a factor of heat regulation in the ecosystem utilising the radiated energy in an alternative way.

Last but not least, the role of wind should be commented. It is a general experience that 60% of the 10 m/s wind speed is traced within the maize population. In a plant stand, the speed of the wind declines logarithmically and may be reduced to 1–2 m/s in the densest canopy. This rather low value influences, i.e. increases the intensity of transpiration too. At the same time the humidity of the atmosphere is lowered effectively.

The appearance and intensity of transpiration are thus the result of several effects. Within the limits of physically determined conditions the possible combinations are many, but also the status of the plants should be considered in any case.

Water uptake of the plant is a function of moisture content of the soil around the roots and of the gradient of moisture content of soil further away. *The water transport of the plant* is a topic seldom dealt with; all the same, it is an important aspect of plant life. Water migrates from within the soil towards the surface and into the atmosphere through different physical conditions (liquid as well as gaseous state). In the tissues and water transport system of the root, stalk and leaf, the differences in pressure move the water upwards to the plant organs, among those the leaves. The speed of transport depends on the differences of pressure (atm). While in the roots, the sucking effect is due to –1 - –5 atm, which increases gradually going upwards into the shoot system and leaves. In the mesophyll tissue of the leaf, the pressure may attain –25 atm if the water supply is scarce. The conditions of water-potential in soil, root, stalk, leaf and air are demonstrated in the sketch of *Figure 2.30*. Within the plant, the chemical potential or sucking force of water is moderate, whereas that of the air – its negative water potential – depends on the temperature and relative humidity. The gradient of pressure regulates the speed of water transport in the plant.

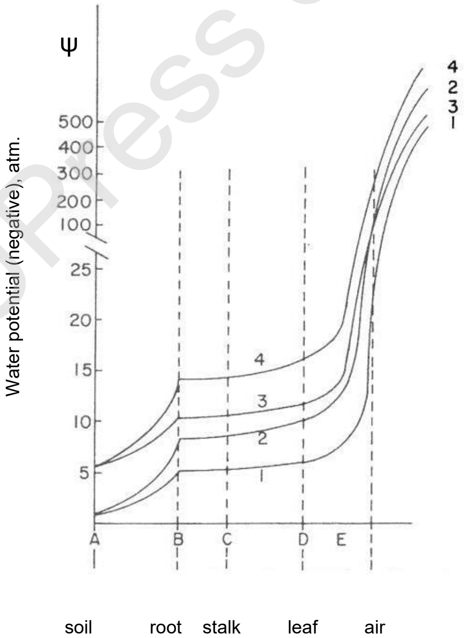

*Figure 2.30* – The vertical distribution of the sucking force in the soil-plant-air system. (Source: *Hillel* 1973)

Function 1 of Figure 4.30 represents the case when the sucking force of the root is weak. In the leaf tissues a strong negative potential is built up and subsequently the turgor and the speed of the water stream declines and wilting of the leaf ensues. Functions 2 and 3 of the figure show the case when the sucking is strong in the soil, but there is a low level of transpiration because of the high relative humidity of the air. Function 4 shows another case, where the sucking force of the soil is low and the plant is already wilting because the lack of water. The conclusion could be drawn: *the speed of water flow in the plant is induced on the one hand by sucking force of the soil and on the other hand, by water deficit in the atmosphere and by higher temperatures.*

In practice, the concept of *climatic water deficit* is an often-used parameter which expresses *the difference between the true and potential evaporation*. As the true evaporation is determined by the natural water supply, it would be more adequate to use the value of the climatic water balance, which deals with the difference between the monthly precipitation and the potential evapotranspiration. In Hungary, this parameter is widely used. As an example, we refer to *Table 2.5*, which shows the magnitude of differences as an average of 50 years. The data show that the values are sometimes positive and sometimes negative because of the high variability of precipitation. During the summer season water deficit may attain excessive values around July and August. The values during winter show that water is stored, whereas the negative values signal the frequent occurrence drought periods.

*Table 2.5* – The frequencies of differences between the monthly sums of precipitation (P) and of the potential evapotranspiration (PET) in Debrecen 1901–1950

| | P < PET | | | | | | | | P > PET | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | –160 | –140 | –120 | –100 | –80 | –60 | –40 | –20 | +20 | +40 | +60 | +80 | +100 | +120 | +140 |
| I. | | | | | | | | | 28 | 48 | 18 | 4 | – | 2 | |
| II. | | | | | | | | | 44 | 28 | 20 | 4 | 4 | | |
| III. | | | | | | | 4 | 32 | 30 | 16 | 8 | 10 | – | | |
| IV. | | | | | 4 | 12 | 22 | 18 | 20 | 18 | 4 | 2 | | | |
| V. | | | 6 | 10 | 16 | 22 | 16 | 20 | 4 | 4 | 2 | | | | |
| VI. | | | 14 | 10 | 28 | 14 | 12 | 10 | 8 | – | 4 | | | | |
| VII. | 2 | 16 | 14 | 22 | 22 | 10 | 2 | 4 | 6 | 2 | | | | | |
| VIII. | 2 | – | 14 | 30 | 18 | 12 | 6 | 2 | 10 | 6 | | | | | |
| IX. | | | | 6 | 16 | 26 | 26 | 8 | 10 | 2 | 4 | 2 | | | |
| X. | | | | | | 4 | 18 | 20 | 18 | 20 | 10 | 4 | 6 | | |
| XI. | | | | | | | 2 | 6 | 16 | 38 | 20 | 12 | 4 | 2 | 2 |
| XII. | | | | | | | | | 16 | 48 | 24 | 4 | 2 | 4 | 2 |

Source: *Szász* 1968

The climatic water deficit in the summer season may show variable values over the country. In the central part of the Great Plain (Danube-Tisza region, Körös-river region, Southern part of the Great Plain) it may amount 350 mm or more. Going radially to north and east, the water deficit declines gradually because the precipitation increases and the potential evapotranspiration decreases moderately. In SW-Cisdanubia the value of water deficit is less than 100 mm. *Figure 2.31* presents the spatial distribution of the climatic water deficit in the summer season showing its regional values.

The climatic water deficit is the difference between the climatic potential evapotranspiration and the real evapotranspiration. The climatic values refer to a short lawn, but for a maize population different values ought to be calculated. The water deficit of maize during the growing season is about 75% of the climatic water deficit. This value varies between wide limits; therefore the values of real evapotranspiration also vary widely. If the decisive factors and their relative weight are known, the range of daily variation of real evapotraspiration could be duly estimated. The daily variation is moderate at the beginning of the growing season, as the radiation provides relatively little energy for evaporation. At the end of spring and early summer, the energy utilised by the daily evapotransiration increases. In the second part of the summer, a special situation of water management ensues, the energy stimulating the evaporation is still high but the moisture content of the soil is reduced already and consequently the daily variation of evaporation declines. In September, the transpiration in the narrow sense is low, the water content of the plant tissues declines and the rate at which the evaporated water is taken up by the roots also declines.

*Figure 2.31* – The climatic water deficit of maize in Hungary.

(Source: *Magyarország Nemzeti Atlasza* 1989)

The values of climatic water deficit calculated by different methods indicate that the real evaporation does not attain the level of the climatic water deficit, except in excessive cases for a very short time. *The local conditions of the real evaporation depend on the water reserves of the soil.* In Hungary, the moisture content of the soil displays a marked dependence on the climate. In the spring, the data of moisture content show the highest values all over the country. The water content of the soil down to 1 m depth approaches or surpasses the values of saturation regarding the minimal water capacity. In soils of good water management, the water supply in springtime varies yearly around 240–300 mm/m. During the summer, in most cases it is around 150–180 mm/m; although higher values may also occur, it is mainly less than 180 mm/m. During the autumn, due to the exsiccation of soils, the content may become less than 120–150 mm/m or much less in some cases. At the same time the recovery of the water reserves may start often up to 200–300 mm/m. The frequency of values measured in the three seasons of the year over 40 years is shown on *Figure 2.32*.

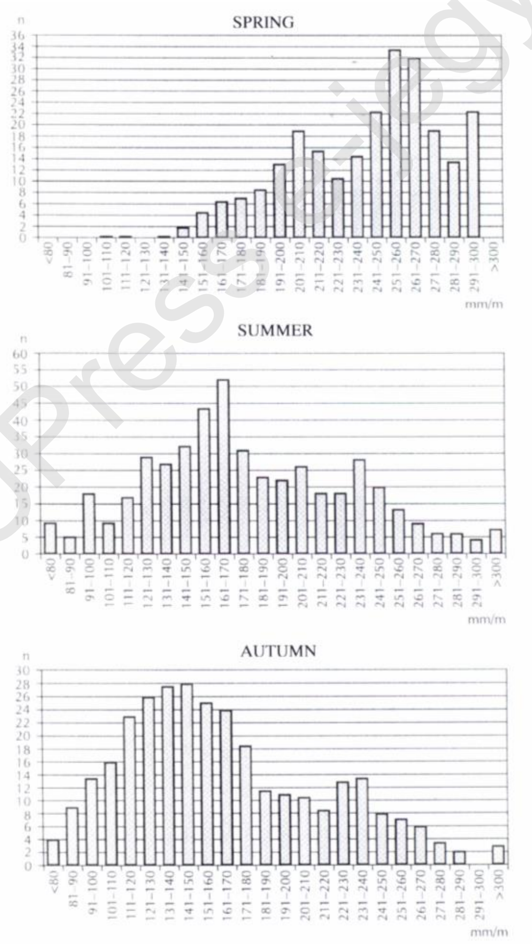

*Figure 2.32* – The mean frequencies of water reserves in loam soils during the three seasons of the year. Debrecen, 1963–2003. (Source: *Szász* 2006)

The maximal speed of exhaustion of water reserves of the soil coincides with the rapidly growing water requirement in the maize crop. This explains the importance of accumulated amounts of precipitation in the three summer months for the provision of maize production. The monitoring of the water supply of soils over whole seasons shows that while in June there are still water reserves at average precipitation around 150–200 mm/m, in July the reserves diminish to 140–170 mm/m. At the end of summer, in August, the reserves continue to decline. The process of exsiccation during the three summer months is visible in *Figure 2.33* in a solution of 10 mm intervals.

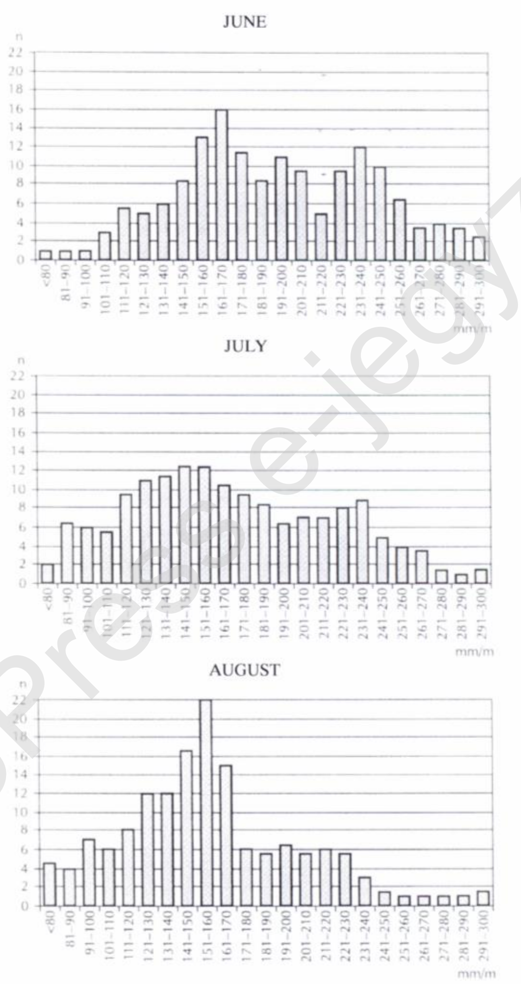

*Figure 2.33* – The frequencies of different moisture content (mm/m) during the three summer months.

(Source: *Szász* 2006)

The analysis of values of moisture content facilitates the estimation the possible values of real evapotranspiration. The necessity of this is based on two arguments. In the practice of production, the distinction between regions is of great significance. The step by step investigation aims firstly at the assessment of parameters which informs the water supply due to the precipitation, being also aware of the supply accumulated or depleted during the previous months (XI–IV). As the moisture of the deep layers of the root zone is derived from the precipitation of the winter and early spring, the data of the mentioned period are especially important from the point of view of deep rooting plants. The water supply of the summer is expressed by the sum of water content in the 0–2 m soil layer and the precipitation of the spring and the summer and we must subtract the values of the potential evapotranspiration of the same period. The values expressing the water supply depend on the conditions of the respective hydrological cycle, which produces the amount of water for the crop. The time scale comprises nearly a whole hydrological cycle. The summer is only the last part of this cycle, and the available amount of water depends on the strict regularities of water management. The results of the calculations are introduced in an empirical scale divided by even intervals. Those are drawn in *Figure 2.34* on a 110 year long time scale, where two seasons are demonstrated. One is a rainy and the other a dry year. By means of this Figure the values could be estimated within the limits of the two extremes. The values of water supply in the summer are divided into eight categories in Hungary. From the data of the two stations, we may estimate the percentage probability for either dry or rainy growing sites.

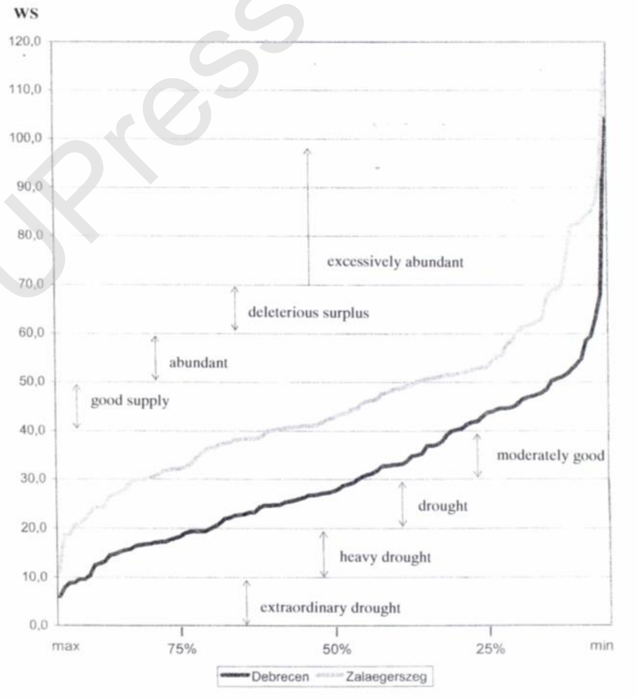

*Figure 2.34* – The frequency curve of water supply during the summer (VE) 1881–1992.

(Source: *Szász* 2002)

The results of the examination demonstrate convincingly that the consequences of the real evaporation may produce different consequences as compared with the climatic parameters. It is well known in practice that the limits of the moisture content of soil are determined by the precedents of the respective season; consequently, valuable estimates are possible. However, the soil is heterogeneous and the local values of moisture content are highly subject to the way of previous utilisation of the area. Local conditions are influenced by changes in the root system of plants during the growing season, which is also genetically determined. Temporary changes of the root system of maize are expressed by its peculiar formation. The majority of roots are concentrated in the upper 0.5 m of the soil, but some roots grow to a depth of 2 m. The development of roots is associated with the growth of the shoot and both attain their maximum extent at the end of flowering. We have to emphasise that the root mass and its activity are different phenomena. The older roots are found in the upper region, but the most active root zone penetrates gradually to deeper layers. At the time of flowering, the most active roots are in about 100 cm depth or even below. That is because the water reserves of the winter are a valuable source of water. The summer precipitation cannot penetrate into the deeper regions. Although the bulk of roots are near to the surface, the activity of the few roots at considerable depth is important in the middle of summer. *Figure 2.35* shows the maximal water uptake of roots at different depths during the growing period at their age expressed in days after emergence. The yearly variable growth and activity of roots affects also of course the extent of transpiration of the plant. Not only the moisture content but also the extents of the active roots determine the water uptake of the plant.

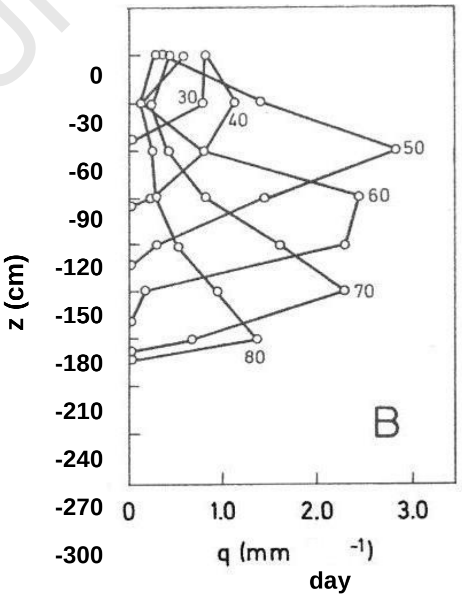

*Figure 2.35* – The maximum of water uptake by the roots at different depths according to the age of the plants in days after emergence. (Source: *Szász* 2006)

The moisture content in the vertical profile of the soil in a maize field is rather peculiar especially if the water table is relatively deep (>3m). Under similar conditions, the water supply of the root zone is subject mainly to climatic factors, and determines the values of evapotranspiration.

### *2.3.6.4. Evapotranspiration of a maize crop is limited by the water available*

*The true evapotranspiration is a parameter of water circulation, which is determined by many factors,* its values are limited to the interval 0.0–PET mm, its maximum being the potential evapotranspiration (PET). Out of the PET, properties of the plant and available water supply of the soil are the main factors which should be factored into the calculation of the real evapotranspiration. The possible daily variation of the true ET is low in the spring, but gradually increases with the increasing energy of solar radiation. The highest variability ensues in the mid summer – July – when evaporation achieves the maximum and the water reserves of the root zone are not yet exhausted. The difference between the potential and the true ET means the absolute value of the water supply, whereas their quotient means the relative value of water supply. The true ET involves many parameters; therefore the same value of water deficit may involve very different causes.

The data of the mean true ET in maize has first been calculated and published with reference to the chernozem soils of the Hajdúhát. The main characteristics are presented in *Table 2.6*.

*Table 2.6* – Potential (PET) and real (TET) evapotransiration in maize plantations as their monthly and daily means

| Month | IV. | V. | VI. | VII. | VIII. | IX. | Total | |
|---|---|---|---|---|---|---|---|---|
| $\mathrm{PET}_K$ | 75 | 99 | 110 | 122 | 118 | 61 | 585 | mm/month |
| $\mathrm{PET}_K$ | 2.5 | 3.2 | 3.7 | 3.9 | 3.8 | 2 | 19.1 | mm/day |
| $\mathrm{TET}_K$ | 48 | 52 | 69 | 93 | 71 | 42 | 375 | mm/month |
| $\mathrm{TET}_K$ | 1.8 | 2.0 | 2.6 | 3.5 | 2.5 | 1.4 | 13.8 | mm/day |

Source: *Szász* 1982

In the comparison of monthly and daily values of potential and real evapotranspiration, it is evident that the potential ET surpasses substantially (by 50–70%) the true ET, while during the period of high rates of water consumption, before and after flowering, true ET approaches (around 81–91%) the level of the potential ET. Those rates appear in the majority of cases except where a continuous water uptake was prohibited by an extreme water deficit. The data presented suggest that water circulation of maize is largely limited in Hungary. The extent of that restraint is best expressed by the ratio $TET_K/PET_K$, which is considered to be a specific trait of maize. Climatic conditions modify the value of the ratio, not so much the actual precipitation but rather that of the previous winter. Finally, the sum of precipitation of both periods, of the previous plus the actual precipitation are closely correlated with the ratio.

The development of stress due to water deficit (TET/PET) has been traced meticulously. Maize consumes firstly the water reserves of the upper root zone during its juvenile growth. With the approaching flowering time, water uptake is shifted to deeper regions of the soil. This is clearly demonstrated by the examination of the soil profile at the time following flowering. A host of measurements demonstrate that drying of the soil ensues first in the upper 0–40 cm layer during the growing season. Subsequently, the dry zone extends to the deeper region. After flowering and at the initial period of ripening, the driest layer of the soil is located at a depth of 100–140 cm, if the active soil is deep enough and the water table underneath is not too deep. That special configuration of water management is developed only in seasons when the amount of precipitation did not attain the level of a sufficiently copious water supply. We may conclude that the seasonal patterns of precipitation are responsible for the peculiar stratification of water content in the (sub) soil. Nevertheless, those conditions are immediately decisive in the regulation of daily and several-day-periods of true evapotranspiration.

In summary, we may state that the water requirement and water consumption of maize may be estimated duly by means of the ratio between the data of potential and true water deficit, also referring to the energy supply of the plant. According to long-term field experiments in different maize growing regions, relationships between the balance of radiation, the climatic real evaporation and the water consumption of maize during the growing season have been determined with due accuracy being aware also of detailed information concerning the precipitation of the season. Those values serve mainly for orientation. In different growing sites, the values describing the real water consumption vary between very wide intervals. Different agrotechnical interventions immediately influence the water consumption. The effects of planting density and the nutritional status of the plantations are especially important. With increasing supply of nutrients, especially of nitrogen, the water requirement increases. As for the description of water requirement of maize, the values, intervals and correlations of general validity must be observed absolutely in planning, development as well as in choosing alternative methods.

## 2.4. The growing season of maize

One century ago, *Cserháti* (1901) stated that late maturing varieties are not recommended to the growers in spite of their higher yielding potential. The ears ought to be ripe at the growing site with reasonable reliability. The length of the growing period may vary substantially at different geographical sites (*Jugenheimer* 1958). *Andrejenko* & *Kuperman* (1961) assigned maize hybrids into three groups according to their growing period. Hybrids of a short season require 55–65 days; the medium group 110–115 days, whereas for the longest, 160–230 day-long growing periods are needed. In 1954, the FAO on the *VIIth Congress for maize and sorghum* decided to introduce the FAO number (*Jugenheimer* 1958). The FAO number comprises three digits, the FAO 100 is the earliest, 999 the latest of the group. The first digit appertains to the group, the second digit to the position within the group, whereas the third indicates the type of the kernel. At present the meaning of the third digit has lost its significance because everywhere yellow and dent type kernels are grown.

The FAO number (growing season) is composed by the following standards to be observed in the same experiments:

- 50% female flowering,
- standard average at 25% moisture content,
- standard average at 20% moisture content,
- moisture content at harvest

For each FAO number a linear function is calculated taking the number and the mean of parameters of the growth period. If we substitute the parameters of a hybrid, the FAO number of the given year may be computed (*Szieberth* 2001). According to studies, the length of the growing period may differ in a given year by 10–20 days from that determined by the respective FAO number (*Váczi* 1973).

For a more precise assessment of the growing period, *Lehenbauer* (1914) made the first attempt. He analysed the environmental effects on the growth of maize and approached by this way the length of the growing period. The interrelation between the temperature and the growth of maize was expressed by a quadratic equation. Based on these results, the National Weather Service developed the GDD (Growing Degree Day) method which calculates the length of the growing period with the use of daily mean temperatures above the threshold temperature of 50 °F [10 °C]. *Brown* & *Goodman* (1976) modified the GDD method substituting it with the GDU (Growing Degree Units), but the complicated computation prohibited its general use.

The heat unit and the sum of heat are parameters needed for the description of development and growth of maize from germination until physiological maturity (*Józsa* 1981). There are different methods for the calculation of heat units. *Cross* & *Zuber* (1972) developed 22 methods for the calculation of heat units in maize growing. *Tollenaar et al*. (1979) dealt with four alternative methods for the same purpose. The Ontario Corn Heat Unit Method was considered to be the most accurate. *Derieux* & *Bonhomme* (1982) compared seven alternative methods of heat unit calculations and concluded that there was no significant difference among them in finding the length and variance regarding the length of growing period. The relative variance of the hybrids examined was around 6.6–6.8% regarding the length of growing periods. The variance increased significantly (by 16.7–20%), if the time between planting and physiological maturity was calculated simply in days.

The weak point in calculating the heat units is finding the threshold value of temperature. In the GDD the lowest temperature is 10 $^oC$, but several authors (*Gilmore* & *Rogers* 1958, *Arnold* 1975, *Bloc* & *Gouet* 1976, *Bunting* 1976) proposed other values of temperature. In Europe the use of 10 $^oC$ gained confidence (*Derieux* & *Bonhomme* 1982).

One of the defects of the heat unit method is that it ignores the different requirements regarding the minimum temperature of the successive phenophases during development (*Andrejenko* & *Kuperman* 1961, *Ábrányi* 1988). The temperature minima have been studied by means of a temperature scale camera in several hybrids and inbred lines of maize. Germination started in two hybrids at 4 $^oC$, whereas in more exigent hybrids and inbreds the threshold was at 8 $^oC$. They concluded that a generally valid threshold could not be fixed for maize; each genotype may have its own (*Stamp* 1984, *Herczegh* & *Marton* 1986).

In spite of these difficulties, for the quick and reliable characterisation of the length of growing period, the estimation by means of heat units is more suitable than by means of calendar days (*Derieux* & *Bonhomme* 1982, *Marton* 1990). The growing period was divided into vegetative and generative parts firstly by *Gunn & Christensen* (1956). The vegetative period is from planting to female flowering, the generative from there until harvest. Several authors addressed the question of stability and variability of those phases of growing period (*Andrejenko* & *Kuperman* 1961, *Aldrich & Leng* 1972, *Menyhért* 1975). Significant differences seemed to be mainly in the vegetative phase.

*Hanway* (1963) determined the first half of development until female flowering on the basis of the number of leaves, whereas the subsequent half was divided and distinguished by means of kernel development. However, the whole growing period was divided into 11 phases (*Table 2.7*).

*Table 2.7* – The phases of growth in maize. (Source: *Hanway* 1963)

| | planting | emergence | 4. leaf | 8. leaf | 12. leaf | 16. leaf | fertilisation | fertilisation 12. day | fertilisation 24. day | fertilisation 36. day | fertilisation 48. day | fertilisation 60. day = | harvest |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of days | | 9 | 13 | 37 | 51 | 65 | 75 | 87 | 99 | 111 | 123 | 135 | 145 |
| Scale | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |

*Hallauer* & *Russell* (1961), as well as *Hanway* (1963) stated that the time elapsed between female growth and the maximal accumulation of dry matter is relatively constant, consequently it may be utilised for predicting the date of maturity. The generative part of the growing period has been divided by some authors into several phases. *Kiesselbach* (1950) divided the generative phase into five parts based on set per cents of accumulated dry matter. *Johnson* & *Tanner* (1972) defined three parts, *Fótosné* (1983) four parts regarding the period of dry matter accumulation. All three authors described the rapid accumulation of dry matter as a linear equation. *Derieux* (1975) and *Dobos* (2003) divided the generative growing period of maize into three phases: flowering – water content maximum (35–42 days), water content maximum – dry matter maximum (63–77 days), the phase after the dry matter maximum (*Figure 2.36*).

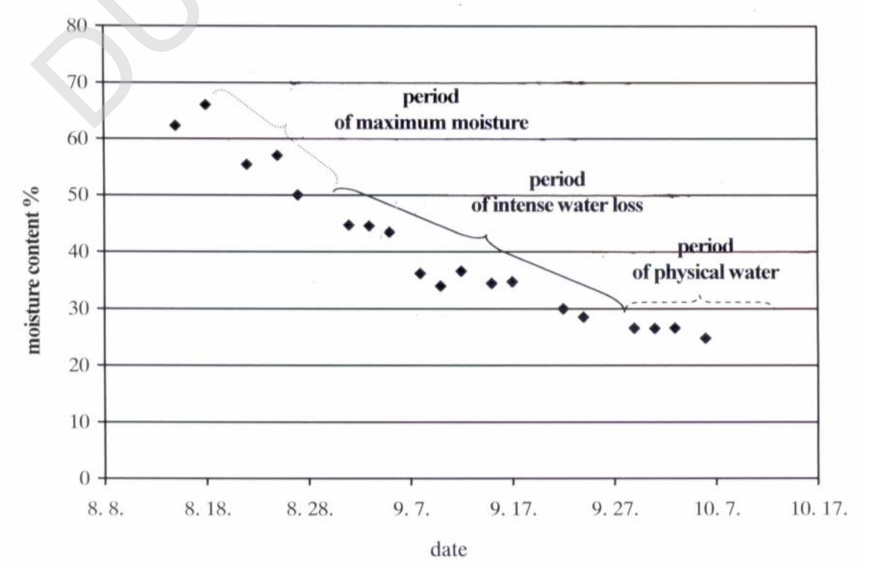

*Figure 2.36* – Phases of the loss of moisture content of maize kernels. (Source: *Dobos* 2003)

### *2.4.1. The heat requirement of maize and the heat sum*

Maize requires heat, which is explained with its origin. In Hungary, those growing sites where maize can be grown successfully are those where the heat (thermal) requirements of maize are met. The thermal requirement of maize is genetically fixed; therefore low and variable yields are expected where the climate is not adequate. The thermal requirement takes two forms, the temperature and the temporal sum of heat. The latter is expressed essentially in the phenomenon of photoperiodism. Maize is a short-day plant, which means that fruit is produced only at daylengths shorter than 15 hours. Hungary is somewhat more in the northern latitude of the maize growing zone, which means that photoperiod is an important environmental factor determining the speed of development of the maize plant (*Schütt* 1972). As for its photosynthetic activity, maize is a $C_4$ plant, which means that the threshold value of effective light intensity is very low. As the processes which regulate photoperiodic effects depend on the special wavelength of the radiating energy (which we may consider as a special case of temperature effects), the heat requirement of maize cannot be separated from the photoperiodic effect.

Photosynthesis is a heat-dependent process, which means that temperature is one of its regulators. The effective temperature is approximately the interval 5–35 °C. Different parts of this interval are associated with various rates of increment of dry matter. The temperature-dependent growth curve was described by *Lehenbauer* (1914) by means of exact experimental proofs, which have been confirmed since then by several authors. Effects of the increasing temperature are initially low, but after the three-leaf stage until flowering, an increase according to a linear equation of increasing speed of development is experienced. The temperature determines the speed of development linearly within the interval of 10–30 °C. That high dependence on temperature has been demonstrated by different methods.

The geographic expansion of maize growing ensued within a relatively short time compared with other cultivated plants, which is one of the reasons why the temperature effects should be studied more intensely. It was stated that independently from the optimum temperature, we should also know the threshold temperatures which are associated with the linear section of this equation. Detailed studies endeavoured to find the lower, so-called base, temperatures in European and American regions of maize production. The base temperature could be considered as a kind of biological zero-degree, where without lethal effect with the approach of this point the speed of development slows down considerably. The curve of the temperature-dependent development of maize has a very peculiar form: between the base and optimum temperatures there is a domain of relatively low linear efficiency, whereas above the optimum a relatively short interval stops growth drastically, moreover, above 35 °C, deleterious processes are a threat (precipitation of proteins). In *Figure 2.37,* temperature dependence of a Hungarian maize variety with a medium length of growing period is shown. It is stated that at the upper temperature limit – "the ceiling temperature" – growth was not observed, moreover, significant processes of degradation appeared. It evident that the distribution of maize growing areas in Hungary mirrors the thermal requirement of maize.

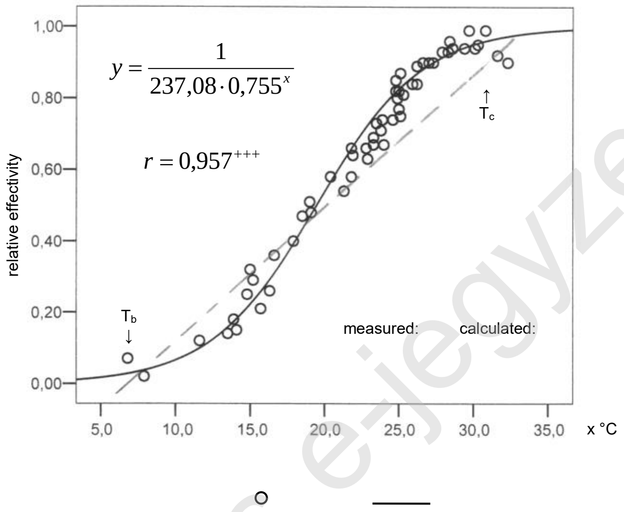

*Figure 2.37* – The development of maize as a function of temperature at the phases of emergence and of male flowering. (Source: *Szász* 2006)

The data presented are fully acceptable only if we postulate that the temperature of plants is identical with that of the surrounding air, which is of course a transitory condition. Under field conditions, the *temperature of the plant* is higher or lower than that of the air depending on its water supply. The experiences of growers as well as results of field experiments and proofs raised in the laboratory indicate the outstanding role of water supply in thermo-regulation. As far as the water reserve is deficient and the water circulation is limited, the temperature of the plant may increase above that of the air. The opposite is expected if the transpiration of the leaves is high as evaporation from the leaves absorbs heat. *The temperature of the plant may vary around that of the air within an interval of ± 2-3 °C depending on the water supply.* As a matter of fact, the difference is not large in the absolute sense; however, a prolonged drought may exert a significant and accumulated effect, which may have severe consequences. The different temperature of the plant and the air – as observed later – influences the speed of growth.

*The role of temperature is observed continuously over the whole growing period.* During the vegetative phase it is an important factor of the speed of growth whilst later, in the generative phase, its decisive role is recognised in the processes of translocation. More complicated compounds are synthesised carbohydrates more rapidly at higher temperatures. We do not want to go into details of biochemistry but is well known that the signs of the heat requirement are revealed in different ways, among others in the water circulation of the plants. Transpiration itself is an energy consuming process but its speed depends on the temperature of the respective organ of the plant.

The heat requirement of the plants was already recognised by *de Reaumur* in 1735 who, by summing the daily mean temperatures, concluded that *the heat sum is related* to the developmental stage of plants. From this analogy one may conclude from the size and stage of the plants the temperature of the previous period. This observation founded the basis of *phenological diagnostics*. In this relationship, the necessity of setting limits on the effects of temperature, the so-called base temperatures emerged. The same idea was recognised by *de Candolle* in 1865, but its application for maize ensued much later and was coined by the study of *Gilmore* & *Rogers* (1958) and of *Arnold* (1959, 1960). It is still relevant, especially the determination of the lower or minimum base temperature, which is critical from the point of view of the planting time of maize, as the nocturnal minima impair the development. The cited authors considered 10 °C to be the base temperature of the daily mean assuming that the nocturnal minima are not too low, i.e. damaging to the plants. It turned out later that the "biological zero" is not a fixed value of general validity and changes according to the regions of different climates. Thus the respective value is after *Tollenaar* & *Hunter* (1983) in Canada 12 °C, while in southern France, indicated by *Derieux* & *Bonhomme* (1982), 8 °C or 6 °C. The general conclusion is that the warmer the climate, the lower minimum base temperatures should be recommended. Those statements are base on the results of practical observation.

The sum of temperatures, which is the sum of the differences between the upper and lower base temperatures as the abscissa of the function of speed of development of maize is a linear equation. The so-called *temperature sum* is the sum of daily mean temperatures of a set period and the fraction of this variable referred to one day is the so-called degree-day. We should emphasise that the linear function is valid only over a longer period. Essentially, this hypothesis is unacceptable because the physiological effects of temperature are logarithmic, not linear. If we disregard the rigour of that rule we may postulate that *with the passing time and increasing values of the temperature sum the accumulation of the living volume of the plant will be a linear process.* Thus we mean that the process is mainly linear, but if we are more accurate, we must admit that there are also signs of non-linear effects, which will be dealt with later.

If the rule of the temperature sum is accepted, the length of the phenological phases or the developmental stage of the plant would be predictable. The essence of this method is the acceptance of the hypothesis that the respective function has only one parameter. It is presently widely accepted in spite of the fact that the concept itself is a physical contradiction. We cannot disregard the inaccuracy of summing readings of mean temperature. Temperature is a continuous element of weather, and the daily means are not independent variables. The other contradiction stems on the fact that the units (°C/time) cannot be regarded as units of energy. The sum of temperature and degree-day are empirical indices, which have a poor theoretical justification. A method of determination based on defective principles cannot be improved. It is also a matter on which to reflect that the effect of heat is not a linear process, and photoperiodism is also a special case of heat effect, which is expressed by another parameter. However, the analysis of that problem is not our purpose. Consequently, we have to describe a non-linear function by a linear equation, thus the result is a so-called curvilinear function, i.e. the function of a higher order is substituted by a linear function. The use of the curvilinear method in describing biological processes has the handicap of restricted validity, namely, average conditions have to be assumed.  The value of degree-day cannot be considered taken as a reference for any day of the phenophase in question because it is continuously changing with the warming trend of the climate, e.g. the phase between crop emergence and female flowering appears as a linear process although the change of the temperature itself is not linear. The value of the degree-day is specific for varieties or for hybrids and is subject to the whole length of the growing season. As the length of a degree-day depends on the temperature, the development of maize planted later during the spring will be accelerated as a consequence of higher temperatures than for the same variety planted earlier, thus the value of the respective degree-day will increase too. The consequence is that the prediction of flowering dates will be jeopardised.

Thus the computation of the sum of temperature should be performed according to *Gilmore* & *Rogers* (1958), *Arnold* (1959, 1960), moreover, to *Cross* & *Zuber* (1972) by the following formula:

$$\sum_{1}^{n} T_a = \left( \frac{Max - Min}{2} \right) - T_B \quad {}^{\circ}C$$

where $\Sigma T_a$ is the sum of the active temperatures throughout the growing season, and the expression of the fraction which corresponds to the mean value of daily mean temperature, and $T_B$ is the basic temperature. The value of the degree-day is obtained by the formula:

$$\text{degree - day} = \left[\left(\frac{Max - Min}{2}\right) - T_B\right] \quad {}^{\circ}C\ day^{-1}$$

The most critical point of the calculation is the setting the value of the base temperature. For that purpose we may choose among alternatives. The most accepted one is proposed by *Gilmore* & *Rogers* based on a regression analysis, which postulates that the growth is linear during the first phase of development – being demonstrated relatively well – and the horizontal axis of the graph is the temperature. The vertical axis is assigned to the volume or height of the plants. The intersection of (linear) growth with the horizontal axis (x) indicates the base temperature. The validity of the results could be checked by tests of significance. Nevertheless, the application of the method needs systematic control over several seasons, which may provide the adequate database.

Another method using a more reliable database is proposed by *Szász* & *Nagy* (unpublished). The distribution of probability of growth over temperature gives an asymmetric β-distribution, hence the β-model of the distribution. In this case, where the linear equation is touching the point of optimal temperature at the five-leaf stage its intersection with the x-axis is the respective value of the basic temperature (*Figure 2.38*).

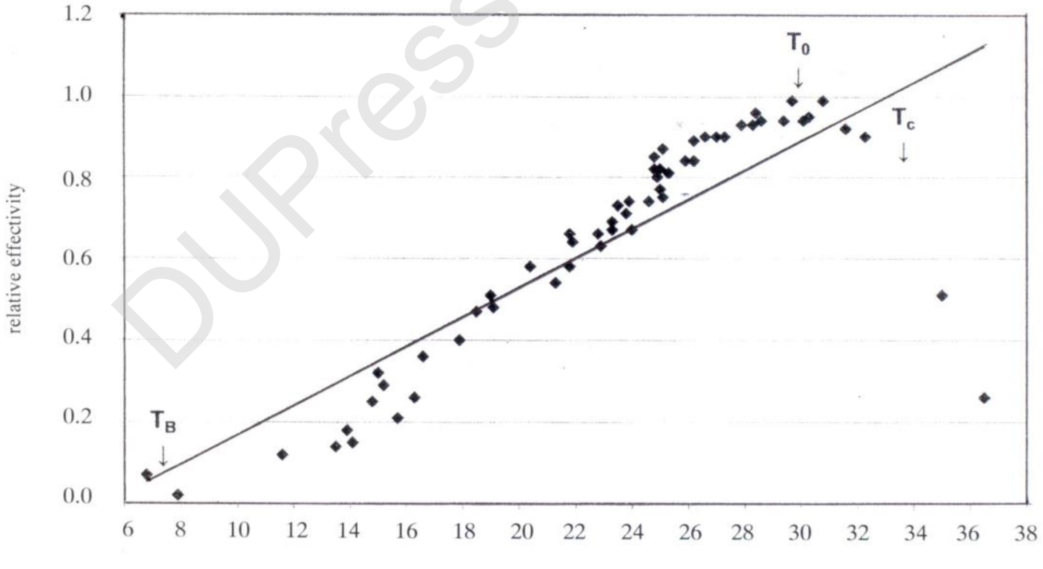

*Figure 2.38* – The curve of development of maize plotted against the temperature $^{o}$C according to the β-model. (Source: *Szász* & *Nagy* 2006)

In that way, the influence of climatic conditions on the value of base temperature could be calculated. It is a proven fact that within the borders of Hungary there is no one base temperature but for each variety and hybrid of various length of growing season, and for each planting date, its own base temperature should be calculated because their heat requirements are different. The duration of taking base temperature into account could be easily shown by calculation of its probability and we should know at a 90–95% probability the occurrence of cases which do not attain the set value of base temperature. In Hungary, calculation with the base temperature should be necessary during the first three, occasionally four weeks depending on planting time.

As far as the daily variation of temperature is **greater** than the base temperature, we must know the lowest temperature where the values ought to be omitted in order to find the sum of temperature. That value is generally found by statistical methods from the database of climatological observations applying an equation of the third order, which describes the variation of the latter value until the end of the flowering period (*Tollenaar et al.* 1979, *Ritchie et al.* 1994). In those cases where the phenological phases are longer, the necessity of finding a proper base temperature is shown in *Figure 2.39*.

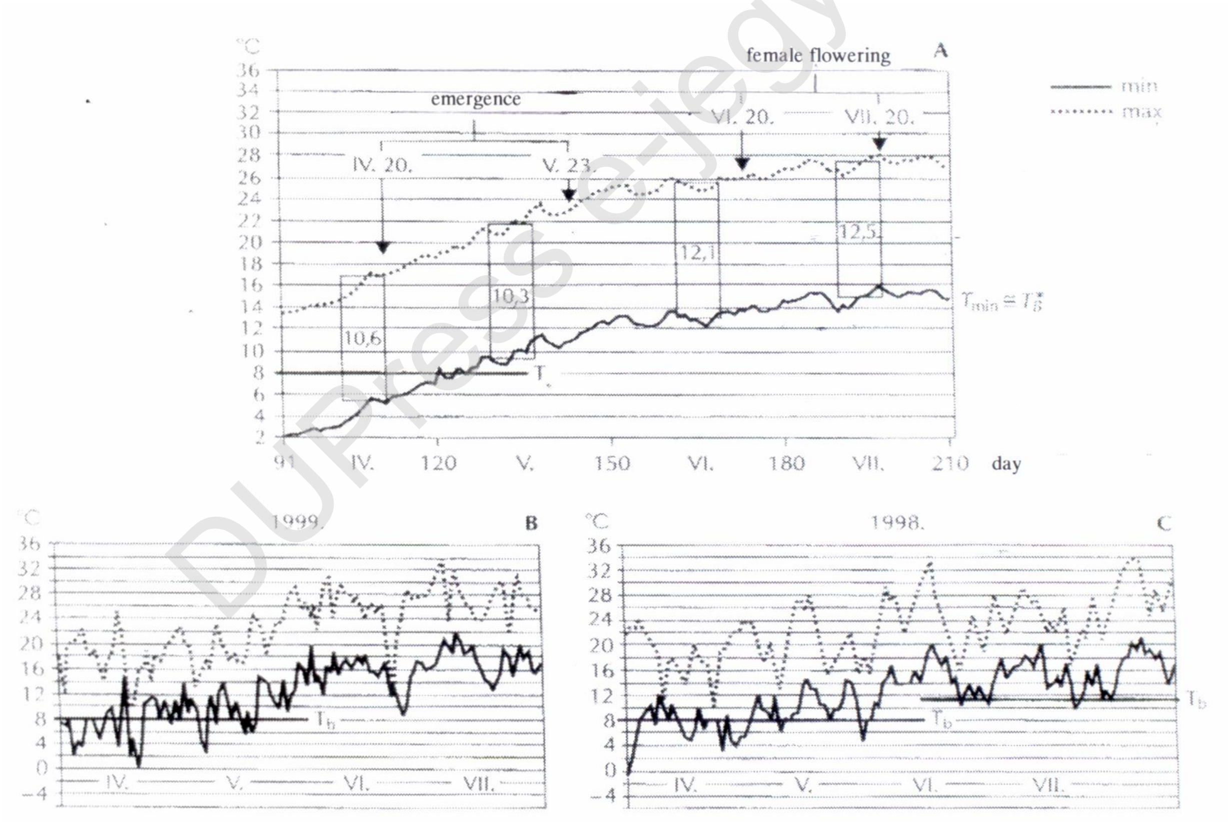

*Figure 2.39* – The emergence and female flowering of maize hybrids examined, and the variation of monthly and daily means of temperature within the same time interval.

(Source: *Szász* & *Nagy* 2006)

The Figure provides a survey in the upper ‘A’ part on the variation of the daily temperature minima and maxima during the vegetative development of maize and makes it clear that the linearity of the function cannot be accepted. The critical values of temperature are represented by the curve of $T_{min}$, which shows lower values than the cited base temperature until about its first quarter. Obviously, the minima below 8 °C ought to be ignored because they are lacking any physical reality. It means also that the base temperature computed from the minima and maxima does not coincide with the really active domain. As the daily maxima are always below the optima, therefore they are accepted as upper base temperature. By a detailed study, it was stated that the mean of the active temperature is not calculated by the formula: $(T_{max}+T_{min})/2$, but rather: $(T_{max}+T_B)/2$, which may prove more realistic as long as $T_{min} < T_B$. The earlier method is loaded with some inaccuracy in cases where the daily means were near 8–10 °C and in similar cases the temperature minima ought to be preferred. In the ’A’ part of the Figure appears the $T_B$ value meaning the minimum and its use is justified for 30 days only. Subsequently a curve of second and third order could describe the lower limit of temperature (‘A’ and ‘B’ part). As an approaching procedure, the part ‘C’ shows the case when in the domain of higher temperatures higher values of base temperatures should be considered in linear functions or some polynomials of higher degrees should be applied.

Around the calculation of the temperature sum emerged some uncertainties in the details, which should be clarified by further examination. The most essential point is that instead of the daily means and its sum, daily variations are considered, which were more typical for almost all growing regions. In part ‘A’ of the Figure, it is evident that in Hungary, 10–12 °C daily variation is nearly constant at least from the point of view of the phenological phases of maize, but according to our studies also in other regions. Detailed investigations were performed in Canada, USA, and in Western and Eastern Europe. Extended climatological analyses laid the foundation that in the region 40–46$^o$ latitude of North America the daily variation of the temperature during the vegetative phase of vegetative development of maize (May-July) was around 12 $^o$C, and the differences between the regions referred to was some tenth of degrees only, whereas in Western Europe – e.g. England, where maize is grown – daily variation is 6.5 °C. In Western Europe the variation it is 10.0–11.0 °C, in Southern Europe 6.0–8.0 °C. After all, the question of base temperature ought to be solved by different approaches in those regions. To the active sum of temperature – instead of the sum of daily means – the variation of the temperature proved to be useful as being more reliable especially if the base temperature would be considered at the calculation of minima. By this method, the problem of curvilinearity may be solved, namely, the non-linear variation of temperature could be ignored because the daily variation seems to be nearly constant, and therefore, they are prone to be handled as a linear phenomenon. For this reason the calculation of the sum of temperature may based on the formula:

$$\sum \Delta T_a = \Sigma(T_{\max} - T_{\min}) = \Sigma(T_{\max} - T_{\min \cdot b})$$

As far as the assessment of $T_{min} < T_B$ should be performed, the base temperature ought to be set, while if $T_{min} \geq T_B$, there is no need to set the value of the base temperature. Statistical tests confirmed that the deviation of daily variations of the active temperature over a set period is lower than that calculated in the traditional way, as $\Sigma\Delta T_a$ is the sum of daily variation of temperature. The application of this method requires, by all means, the checking of the average of variations. This method expresses the temperature effect as analogous with the thermal effect, though the thermal energy is not represented by physical units.

Besides the supply of thermal energy, the expression of the photoperiodic effect would be important. The sum of temperature or the calculated degree-day expresses the mean value of thermal concentration during the growing period. We have to know also what time is needed daily to develop one unit of daily thermal effect. Maize is a short-day plant, therefore the photoperiodic effect is asserted in the northern regions to a much more marked degree and is revealed in a great many forms (*Tollenaar* & *Hunter* 1983). The daily length of the photoperiod and its effects on the development of maize are successfully observed under laboratory conditions, but the susceptibility to the length of photoperiods is recognised also under field conditions among varieties and hybrids. It is revealed in the number of leaves and the length of the stalk. The effective supply of temperature is a product of the heat effect and its length. The level of the expression heat corresponds more or less to the temperature, however, but the computation of the sum of temperature ignores the length of the days. Therefore those two parameters have been taken into account in the study of the supply of heat energy (*Szász* & *Nagy*, unpublished data). The procedure of computation is based on the following relations:

heat- and light-effects = length of days + temperature level;

the general formula expressing the rule in terms of energy:

$$TEU = 1{,}21 \cdot \frac{[D(\varphi) \cdot (T_{\max} - T_{\min \cdot b})]}{c} \quad kJ\ kg^{-1}\ day^{-1}$$

where $D(\varphi)$: the length of days depending on the geographical latitude and the declination of the sun, $(T_{max} – T_{min \cdot b})$: the sum of active temperature, c: the proportion factor,
1.21 kJ $kg^{-1}$ $K^{-1}$: is meaning the equivalent of heat-energy. The value calculated by means of

the latter is a physical parameter, which becomes an additive unit and is handled as a physical parameter being comparable and interpretable in this sense. That value has been considered and called thermo-energetic unit (TEU). Its possible values are summarised in *Table 2.8*.

*Table 2.8* – The possible values of thermo-energetic heat unit (kJ kg$^{-1}$day$^{-1}$) at different temperatures and day-lengths

| daylength | $T_{max}$–$T_{min}$ (°C) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| hours | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 8 | 3.69 | 4.30 | 4.92 | 5.53 | 6.15 | 6.76 | 7.38 | 7.99 | 8.61 | 9.22 | 9.83 |
| 9 | 4.15 | 4.84 | 5.53 | 6.22 | 6.92 | 7.61 | 8.30 | 8.99 | 9.68 | 10.37 | 11.06 |
| 10 | 4.61 | 5.38 | 6.15 | 6.92 | 7.68 | 8.45 | 9.22 | 9.99 | 10.76 | 11.53 | 12.29 |
| 11 | 5.07 | 5.92 | 6.76 | 7.61 | 8.45 | 9.30 | 10.14 | 10.99 | 11.83 | 12.68 | 13.52 |
| 12 | 5.53 | 6.45 | 7.38 | 8.30 | 9.22 | 10.14 | 11.06 | 11.99 | 12.91 | 13.83 | 14.75 |
| 13 | 5.99 | 6.99 | 7.99 | 8.99 | 9.99 | 10.99 | 11.99 | 12.99 | 13.98 | 14.98 | 15.98 |
| 14 | 6.45 | 7.53 | 8.61 | 9.68 | 10.76 | 11.83 | 12.91 | 13.98 | 15.06 | 16.14 | 17.21 |
| 15 | 6.92 | 8.07 | 9.22 | 10.37 | 11.53 | 12.68 | 13.83 | 14.98 | 16.14 | 17.29 | 18.44 |
| 16 | 7.38 | 8.61 | 9.83 | 11.06 | 12.29 | 13.52 | 14.75 | 15.98 | 17.21 | 18.44 | 19.67 |

Source: *Szász* & *Nagy* 2006

According to the data of the Table, we see the values of TEU expressing the heat supply by two parameters, which is susceptible to both the length of the day as well as the temperature. Looking at the values of the Table, we may observe that with the increasing temperatures the role of daylength gains importance gradually. At low temperatures, within the interval 8–16 hours, at 6 °C the susceptibility to day length is 0.5 kJ kg$^{-1}$ day$^{-1}$, while at 16 °C it is 1.23 kJ kg$^{-1}$ day$^{-1}$. Those values indicate that the photoperiodic effect is much stronger with increasing temperature. On the other hand, the susceptibility to temperature increases exponentially at the same photoperiod indicating that within the domain examined the importance of the heat effect (temperature) increases significantly and it is supposed until the optimum temperature. Under Hungarian conditions, amplitudes of variation of temperature within one day are 10–12 °C, which may be considered to be acceptable. By the extreme values of temperature, the same regularity is expressed in a more accurate way. In experiments where different maize varieties and hybrids are analysed for their susceptibility to heat effects, the method presented may find a successful application. The method facilitates the comparison of many growing sites and the extent of similarity among them could be expressed numerically by means of the value of TEU. The procedure presented is also applicable to the generative phase of development of maize. However, the importance of phenological predictions is first of all used in the vegetative phase especially in planning the start of the flowering period and in comparing the effect of seasons on the development of maize.

### *2.4.2. The accumulation of dry matter and the dynamic of decreasing moisture content*

*Bellini* & *Fusi* (1961) stated that a rate of 43–49% of the total organic dry matter of the maize plant is in the kernels. The process of filling of the kernels is closely correlated with the loss of moisture content and both are influenced by a host of factors. *Kiesselbach* (1950) claims that temperature and water supply are significant conditions for the successful development of kernels. Temperature and speed of kernel development are positively correlated (*Duncan et al.* 1965). A similar positive correlation was registered by *Ragland et al.* (1965) between temperature and ear development.

The maximum dry matter content of the kernels ensues when the black layer appears in the kernels as a sign of physiological maturity (*Carter* & *Poneleit* 1973). The black layer is developed underneath the testa (skin of the seed) at the base of the seed, where the cells of the conjective tissue died. The dead cells impair translocation but some compounds may still penetrate the black layer (*Duffus* & *Cochran* 1982). Low temperature and unfavourable supply of organic compounds stimulate the development of the black layer (*Daynard* & *Duncan* 1969). Frost damage ensuing before physiological maturity stops the accumulation of dry matter and causes loss of yield as well as reduced quality (*Józsa* 1981). At the period of kernel filling, the high temperature and defective accumulation of sugar (saccharose), the of the black layer appears earlier at a low maximum of dry matter and a high moisture content (*Afuakwa et al.* 1984, *Hanft et al.* 1986). Temperature and provision of organic compounds are also decisive in determining the time of physiological maturity (*Daynard* & *Duncan* 1969. *Wilson et al.* 1973, *Máthéné* 1989). Cool weather delays (*Hallauer* & *Russell* 1961), high temperature (>30 $^{o}$C) anticipates the time of maturity (*Badu-Apraku et al.* 1983, *Tollenaar* & *Bruulsema* 1988). Low temperature is also unfavourable for dry matter accumulation (*Bunting* 1976) and the yield is more or less reduced (*Jones et al.* 1981). Water deficiency reduces the speed of accumulation of dry matter and delays the time of maturity (*Quattar et al.* 1987a.b).

Water is a normal constituent of the maize kernel fulfilling indispensable functions in physiological processes; and consequently it is a component of the future quality and vigour of the seeds. At harvest, the moisture content of the maize kernel should be 23–24% as optimal for combine harvesting (*Bocz* 1992). The change of water content in maize kernels is divided into two periods: physiological activities are going on during the development of kernels whereas, after physiological maturity, a passive drying process is observed (*Schmidt* & *Hallauer* 1966). The negative correlation between temperature and water content is significant in the intervals 75–50% and 50–30%. During the next interval (below 30% water content), other weather conditions than temperature alone (relative humidity of the air and the lack of saturation) are important conditions too.

*Aldrich et al.* (1975) claim that after physiological maturity, weather is the most important condition. During the development of kernels, the cytological processes, division, elongation, development of inclusions and rest periods follow each other. All phases require water, but water volume increases initially and declines subsequently. The maximum volume of water varies according to the genotype of hybrids and the season (*Figure 2.40*). Within one season, there is no difference between the maximum values belonging to set sums of temperature, being less than 2–4 days. For a given hybrid in a given season, there is a close correlation between maximal water content and length of the generative phenophase (*Dobos* 2003). With a good water supply, the maxima of water volume are high and they are favourable from the point of view of a longer and more intense period of accumulating dry matter.

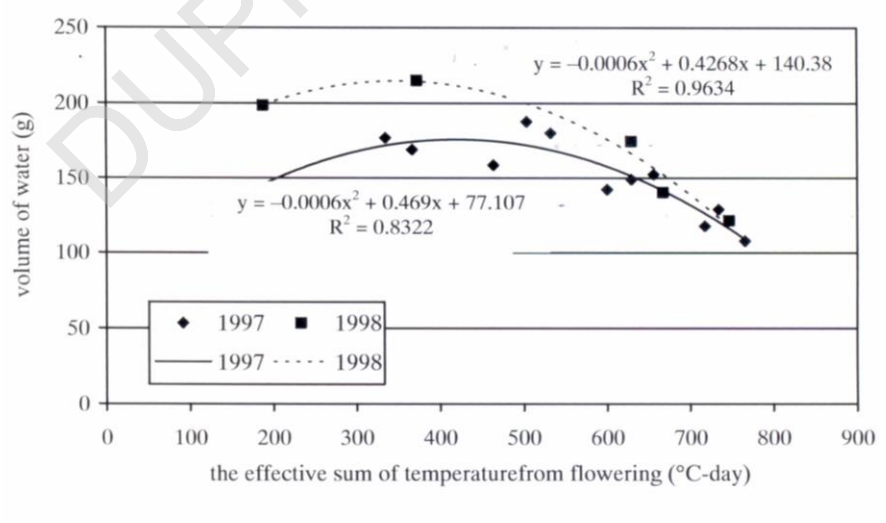

*Figure 2.40* – Water volume of maize kernels in the generative phase of development. Debrecen. 1997–1998.

(Source: *Dobos* 2003)

The moisture content of maize kernels is a reliable index of its maturity (*Hallauer* & *Russell* 1962). There is a close correlation between the loss of moisture content and kernel filling also plotted against the scale of Growing Degree Day (*Kang et al.* 1986). Various hybrids and varieties display different levels of stability regarding the influence of effects associated with environmental conditions (*Hallauer* & *Russell* 1961). The genotypes belonging to a later group of maturity lose moisture at a slower rate but are more exposed to environmental hazards to various extents (*Magari et al.* 1997). Among these the role of precipitation or rather GDD + precipitation and GDD + relative air humidity are decisive in influencing and entering into interaction with the process of water loss in the kernels.

The dynamics and duration of water loss depend greatly on climatic factors. Temperature is the most important among them (*Bloc* & *Gouet* 1974). *Kang et al.* (1986) found a negative correlation between the mass of kernels and the moisture content of the ear (–0.84), however, after full physiological maturation the role of the kernel-mass could be ignored (r=0.04).

Among the visual signs of maturity in the maize kernel, the appearance of the so-called milk-streak (meaning about 40% moisture content) is more reliable than the so-called black layer described by *Daynard* & *Duncan* (1969) according to *Afuakwa et al.* (1984), which is claimed to be associated with physiological maturity. The filling of maize kernels is connected with the loss of moisture content. Until physiological maturity, active physiological processes prevail. *Kang et al.* (1986) showed by means of path-analysis a positive interaction between kernel filling and the speed of decline in water content %, which means that if the speed of kernel filling increases, water loss ensues at a higher rate (% loss per day). The rate of water loss depends also on the type of the kernel (*Derieux* 1975, *Derieux & Bonhomme* 1982), the thick layer of the pericarp (*Purdy & Crane* 1967) and on the quality of the husk leaves (*Crane et al.* 1959). *Neményi* (1983) explored the relationship between water loss with the water-losing inclination determined by some hybrid genotypes and the structure and chemical composition of the pericarp. *Helm* & *Zuber* (1969) also emphasised the decisive role of the pericarp in the loss of moisture content.

In their study which explored the process of drying from the appearance of the black layer until harvest, *Schmidt* & *Hallauer* (1966) observed that the daily rate of water loss depends on the season. *Hallauer* & *Russell* (1962), *Purdy* & *Crane* (1967) and *Sutton* & *Stucker* (1974) reported important differences between lines and hybrids. On the contrary, *Hicks et al. (*1976) and *Dobos* (2003) were unable to show the specificity of hybrids from this point of view. Investigations produced evidence that the loss of moisture is regulated by precipitation (air humidity) as well as by temperature. After the appearance of the black layer, the moisture content may diminish but also increase as a consequence of high air humidity. The linear correlation is well expressed by the high values of $r^2$ as shown in *Table 2.9*.

*Table 2.9* – The dynamic of water loss in kernels of various genotypes of maize hybrids after physiological maturity. Debrecen, 1996–1998

| Hybrid FAO number | Years | | |
|---|---|---|---|
| | 1996 | 1997 | 1998 |
| 270 | –.164X+24.227<br>$R^2$ =.971 | –.153X+20.140<br>$R^2$ =.998 | –.129X+26.332<br>$R^2$ =.981 |
| 310 | –.122X+25.348<br>$R^2$ =.964 | | –.119X+28.690<br>$R^2$ =.937 |
| 310 | –.139X+27.975<br>$R^2$ =.968 | | –.135X+23.728<br>$R^2$ =.829 |
| 380 | –-<br>.123X+25.901<br>$R^2$ =.929 | –.154X+22.607<br>$R^2$ =1.00 | –.129X+26.088<br>$R^2$ =.983 |
| 380 | | –<br>.S136x+29.500<br>$R^2$ =.764 | |
| 380 | –.150X+26.511<br>$R^2$ =.989 | –.112X+25.537<br>$R^2$ =1.000 | |
| 410 | | –.167x+23.706<br>$R^2$ =.545 | |
| 430 | –.164X+29.379<br>$R^2$ =.992 | –.114X+23.489<br>$R^2$ =1.000 | |
| 450 | | –.145x+18.503<br>$R^2$ = .733 | |

Source: *Dobos* 2003

The speed of water loss was similar in the hybrids examined as indicated by the slopes of the regression lines. According to *Pók* & *Szundy* (2003), the process of water loss is genetically determined until the completion of kernel filling, however, after physiological maturity the genetic control changes and the role of environment prevails, therefore excessive precipitation or droughts dissimulate the genetic differences. In drought years, water content declines while the concentration of solutions in the cells increases. Water deficiency causes problems with the physiological processes (*El-Said et al.* 1975).

The majority of agrotechnical interventions (planting density, chemical fertilisation) are designed to increase not only yield but also to reduce the moisture content of kernels at the due date. With the correct application of all those procedures those aims are achieved (*Kising 1962*, *Nagy* & *Zeke* 1981) and the exploitation of water supply is also improved (*Kovács 1982*, *Németh* & *Búzás* 1991, *Nagy* 1996, 1998). *Gagro* (1974), exploring the effects of N fertilisation in relation to the moisture content of kernels, concluded that the lack as well as an excess of N fertilisation (200 kg/ha N) produced the highest water content in the ripe kernels. The same type of study, i.e. exploring the effect of N fertilisation, by *Gotlin* & *Pucoric* (1977) found that increasing doses of chemical fertilisers reduced the moisture content of kernels. One of the effects was the higher crude protein content of the kernels with the reduced moisture content. At the same time, irrigation, especially combined with a low level of nutrients, increased the moisture content of kernels significantly (*Nagy* & *Zeke* 1982).

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**Figure 2.2.** *Zea mays* L.

**Figure 2.3.** Ears of dent corn maize (convar.dentiformis)

(Source: *Nagy* 2006)

**Figure 2.4.** Flour type maize (convar. vulgaris) hard kernels.

(Source: *Nagy* 2006)

**Figure 2.5.** Sweet corn maize with smooth, (convar. saccharata).[1]

[1] Source: *plantnames.unimelb.edu.au/Sorting/Zea.html*

**Figure 2.6.** Pop corn maize (convar. microsperma).[1]

**Figure 2.7.** Waxy maize (convar. ceratina).[1]

**Figure 2.8.** Transitory maize (convar. aorista).[1]

**Figure 2.9.** Ornamental maize (convar. japonica).[2]

**Figure 2.10.** Glumous maize (convar. tunicata).[1]

[1] Source: *plantnames.unimelb.edu.au/Sorting/Zea.html*

[2] Source: *www.seedsavers.org*

**Figure 2.12.** Supporting roots (Source: *Nagy* 2006)

**Figure 2.16.** Female inflorescence of maize. (Source: *Nagy* 2006)

**Figure 2.17.** Male inflorescences of maize. (Source: *Nagy* 2006)

ISBN 978-963-615-073-0