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MAIZE

CEE REGENERATIVE AGRICULTURE GUIDEBOOK

TERRA NOSTRA FUNDACJA

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Co-funded by the European Union

CEE REGENERATIVE AGRICULTURE GUIDEBOOK - MAIZE

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The Terra Nostra Foundation for Agricultural Development was founded in 2019. Its aim is to promote the idea of regenerative agriculture as a holistic resource and environmental management system that takes into account the profitability and competitiveness of the agricultural business in the value chain.

The foundation's activities are based on the knowledge of practitioners and scientists who implement the Integrated Regenerative Production program. It is based on the conversion of farms to regenerative agriculture through training, practical support and the development of a thematic community. The result of the program is the Certificate for Integrated Regenerative Production, which is awarded by an independent certification body - Bureau Veritas. It serves as evidence of regenerative actions on the farm and a way to monitor the environmental benefits of agricultural management, respected by agri-food processors.

The Terra Nostra Agricultural Development Foundation is also the organizer of the International Forum for Regenerative Agriculture BIO_REACTION, which brings together an international group of experts, scientists, farmers and advisors from around the world.

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REGENERATIVE FARMING OF MAIZE

Maize (*Latin: Zea mays L.*) is a species of annual plant in the Poaceae family. It is a dioecious and monoecious species - producing female and male flowers that are found on a single plant. The female inflorescence is a spadix surrounded by bracts on a shortened shoot called the rachis (cob) (Fig. 1). On the cob also grow husk leaves (known as sheaths), which surround the cob tightly. During flowering, the stigmas emerge from the husk leaves, forming the so-called silks, where the pollen released during flowering from the panicle is deposited. The male flower is the tassel located at the top of the stem (Fig. 2).

Once the ears are fertilised, the kernels develop from florets located on the axis of the cob, called the core. Under typical weather conditions, cultivated maize varieties usually produce one mature cob. However, sometimes maize plants with two or even five cobs can be observed in plantations. Multi-cobbing in maize is an undesirable phenomenon and can occur in some years in maize varieties that are sensitive to variable weather conditions. As the grain matures, maize gradually loses its greenness in the leaves and stalks, dries out (Fig. 3 and 4) and the percentage of dry matter increases.

The maturing maize kernels develop a colour typical of the variety and become hard and shiny (Fig. 5). After maturation, kernels enter a period of dormancy.

Figure 1. The female flower of maize is the ear, which emerges from the leaf sheath in the corner at the BBCH 61 stage.
Photo by A. Perzanowska

Figure 2. At the same time that the ears are developing, the male maize inflorescences, panicles on top of the stalks, are developing.
Photo by A. Perzanowska

Figure 3. Once the florets are fertilised, grains begin to develop in the ears.
Photo by A. Perzanowska

Figure 4. As the kernels mature, maize gradually loses its greenness in the leaves and stalks and the percentage of dry matter increases.
Photo by A. Perzanowska

Figure 5. Dehusked corn cob
Photo by A. Perzanowska

1 INTRODUCTION TO REGENERATIVE FARMING

Maize is one of the oldest crops in the world. Originally cultivated in South America, it reached Europe as early as the end of the 15th century as a result of the expeditions of Christopher Columbus.

Maize cultivation spread relatively quickly in Europe and throughout the world. Thanks to the breeding of maize varieties with lower temperature requirements and a shorter growing season, cultivation of this crop has also expanded considerably in recent decades.

Together with rice and wheat, maize is one of the most important crops on a global scale. The International Grains Council (IGC) estimated that world maize production in the 2021/22 season was 1225 million tonnes, while in the 2022/2023 season it was at 1130 million tonnes. According to the US Department of Agriculture's Foreign Agricultural Service estimates, maize grain production in the 2023/24 season will be 1236 million tonnes, indicating an upward trend. More than half of the world's grain maize crop is grown in the Americas (United States, Brazil, Argentina). China is also a significant producer of grain maize, followed by the European Union, India and Ukraine. Maize is also an important grain crop in the rural areas of Southern Africa. Global consumption of maize grain is huge and similar to the global maize grain harvest in size. At the same time, it should be remembered that maize, apart from its important role in human nutrition, is also a major source of feed for livestock (as concentrated feed and a high-energy crop used for silage). For this reason, maize is grown by an increasing number of farms for grain and to make silage. The use of maize silage in animal feed is growing every year thanks to its high-energy content and being easy to digest for ruminants, as well as the better productivity of maize compared to grasses and the easier ensiling of its biomass. The main producers of maize silage include the United States (40.1 per cent share of the global market in 2021) and the European Union, which accounted for 34.2 per cent in 2021. Maize is also used for the production of fuel, or for derived products such as starch and sweeteners, as well as paper and bioproducts such as plastics and cosmetics. In recent years, corn silage has been used as a substrate for the production of digestate, which is used as a fertiliser on farmland.

The greatest advantages of maize as a C4 plant include its adaptability to diverse growing conditions and the highest genetic yield potential among cereals. Its cultivation can thus ensure stable yields, farm profitability and food security in the face of a changing climate.

In regenerative farming of maize, special attention should be given to the correct integration of this crop into rotation with other crops and the use of appropriate agronomic practices so that the chemical, physical and biological quality of the soil is not impaired. For this reason, regenerative cultivation of maize has to take into account the many interrelationships taking place in the crop rotation on the field and in the agro-ecosystem as a whole. Growing maize in a regenerative manner is a way to achieve stable grain and biomass yields from this crop. It involves farming within a balanced crop rotation and fertilisation regime and a regulated soil pH, while paying attention to the multiple relationships between the maize plant and its habitat.

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CLIMATE, NUTRIENT AND SOIL REQUIREMENTS

Maize shows great adaptability to diverse habitat conditions and for this reason is currently grown from 58° north latitude to 55° south latitude.

It also exhibits many characteristics that are associated with its southern origin.

When it comes to morphological structure, maize differs significantly from other crops included in the cereal group. For one thing, it produces a rather extensive root system, consisting of an embryonic root and numerous adventitious roots that grow from underground nodes. The embryonic root, which develops first, as well as several adventitious roots already growing out of the kernel, take up water from the first stages of corn development. Most of the adventitious roots develop later and grow densely just above the nodes, forming characteristic whorls (Fig. 6). Roots growing in whorls reach up to 1 metre laterally. The main root mass develops to a depth of 60-70 cm. Some of the roots, especially in drier soils, can even reach more than 2 metres deep.

Figure 6. The maize root system has a distinctive structure. Brace roots grow from nodes above the soil surface.
Photo by A. Perzanowska

Adventitious roots developed from the nodes that are located shallowest, form the surface root system, which plays an important role in absorbing water even from low rainfall, providing moisture to only a few centimetres of the surface soil layer. This strategy is particularly beneficial for growing maize under low rainfall conditions. Adventitious roots also grow from nodes on the stalk close to the soil surface, forming so-called brace (aerial) roots to support the relatively tall plant against lodging.

Corn has high requirements in terms of light. It is a C4 plant (like sorghum or sugar cane), which means that it makes much more efficient use of sunlight and CO_2 captured from the atmosphere to produce carbohydrates than plants that carry out C3 photosynthesis (most crop plants). In the process of photosynthesis, plants convert inorganic matter (carbon dioxide - CO_2 and water) into a mass of organic matter. In the presence of light (solar energy), inorganic matter is in fact converted into carbohydrates (sugars), which are a source of energy for the plant's biological processes and also the building material of its tissues. C4 plants have higher photosynthetic efficiency and produce biomass faster than C3 photosynthesis plants. Most plant species that do C4 photosynthesis are found in hot climates where access to solar energy is almost unlimited. Such plants can convert CO_2 from the atmosphere into sugars with their stomata closed, which allows rapid growth while requiring little water to produce units of dry matter.

With its high light requirements and large leaf area, as well as the positive response of the plants to good light, maize should not be sown densely. Plants make particularly good use of light energy for their growth when there is good soil moisture and days are warm. If the crop is too densely planted, the chlorophyll content in the maize leaf blades decreases, the photosynthetic efficiency drops and, consequently, so does the biomass production and grain yield. In extreme cases, too much shade can lead to flower sterility (infertility) and ultimately to a lack of grain production.

Maize is a short-day (long-night) plant, which means that its development depends on the duration of the periods of darkness and light during the day. It extends the vegetative development phase if the plants begin to develop in conditions of long days, which in our latitudes is the case as we transition from spring to summer. In this situation, flowering is delayed, which also affects cob and grain development. Under short-day (10-hour) conditions, maize flowers more quickly. To some extent, the response of maize plants to day length is also regulated by the thermal conditions that depend on the regions. In warmer climates, long season hybrids show a stronger response to daylength than early maturing hybrids grown in regions with cooler climates. When corn is cultivated in hilly areas, the plantations should be located on hills or south-facing slopes to provide better light to the plants.

From the very early growth stages, maize is a plant with high heat requirements. Until not that long ago, the cultivation of maize was restricted exclusively to warm regions of the globe. However, in the 1980s, a range of varieties adapted to cooler temperate regions with a shorter growing season were already widely introduced. Corn germinates most quickly at temperatures above 10°C, but modern varieties adapted to cooler climates can germinate at temperatures as low as 6°C. The crop tolerates periodic temperature fluctuations quite well, but when it is cold, maize grows slowly and is more easily affected by diseases and pests. For example, at a temperature of 21°C, the seeds will germinate in just 5-6 days, while at 7-11°C it can take 15-17 days. When air temperatures are above 25°C, maize grows rapidly because it activates the C4 pathway of photosynthesis, doubling the efficiency of the process. However, at the time of flowering of maize, too high temperatures are not desirable, especially if atmospheric drought occurs at the same time. If the weather is too warm and dry, the pollen released from the panicles quickly loses its vitality, which can lead to poorer pollination of the flowers in the cobs and fewer kernels per cob. If the weather is cooler in the periods after flowering and the fertilisation of flowers in the cobs, it delays the maturation of the plants.

Spring and autumn freezes are also very dangerous for maize. Ground frosts during the germination period have a very strong effect on plant growth inhibition, damage seedling leaves and can lead to plant death. Fatal damage to young plants occurs when frosts exceeding -2°C and lower have an effect on plants for more than 1-2 hours. If the plants survive frosts, they have the ability to regrow leaves and regenerate relatively quickly. Frost damage can be seen on young plants relatively quickly, usually as early as two days after the onset of sub-zero temperatures. Young plants appear wilted and the leaves discolour to a light colour. After a few days, the damaged leaves turn dark and die. Corn can resist ground frost better in the early growth phase (up to 6 leaves), as the growth cones are still below the soil surface, than in later phases, when the growth cones are already above the soil. Early autumn frosts cause damage to maize leaves and make the plants vulnerable to fungal diseases. More severe autumn frosts cause plant death.

There is a common belief that maize has low water requirements, which is not entirely true. Compared to other cereals, the species has a relatively low transpiration rate, which represents the amount of water used to produce an adequate unit of dry matter (Table 1). To produce 1 tonne of dry matter, maize will use 256 tonnes of water, while for example the oat plant will use as much as 468 tonnes. However, it should be remembered that maize at the same time produces a large quantity of biomass per hectare, which also translates into a relatively high uptake of water from the site, despite its economic management. The yields of maize grain and green matter are high compared to other crops and are variable depending on the conditions of the location and the varieties' earliness. Dry grain yields (14% moisture content) range from 9-14 tonnes, but sometimes higher kernel yields are reported. However, under worse weather conditions, with improper agrotechnical treatments and on weaker soils, grain yields can be 6-8 tonnes. Green matter yields calculated on a dry matter basis are 15-25 tonnes. By multiplying the maize productivity ranges by the transpiration coefficients, it is easy to see how significant amounts of water are required by maize to produce biomass.

Table 1. Transpiration coefficients for different crop species.

Species	Transpiration coefficient
Maize	569
Sunflower	256
Spring wheat	432
Oat	468
Alfalfa	664

Source: Sulewska (2004)

When soil drought occurs, leaves of corn plants will curl in a characteristic manner (Fig. 7) - it is a mechanism designed to reduce water loss from the plant through transpiration and protect against irreversible tissue damage.

Figure 7. Curling up of the leaf blades during a drought is maize's defence mechanism against tissue water loss and the risk of irreversible withering.
Photo by A. Perzanowska

Compared to other crops, water management in maize requires special attention from the earliest growth stages. The germinating kernels have the ability to draw water from the soil more efficiently than other commonly grown crops, which is a useful quality. The rate of water uptake from the soil at later growth stages is 3-6 times faster than that of staple cereals (such as oats, wheat, barley). Water uptake rate increases as temperature increases. Maize has the ability to absorb water from soil layers reaching 1.5 m and deeper. Rapid and uniform plant germination also contributes to the development of a strong and deep-reaching root system, which will take up water from deeper soil layers during periods with no rainfall. Meanwhile, maize gets much of its water from a system of adventitious roots growing in whorls from soil layers closer to the surface, with the ability to utilise moisture from dew. Hence, water retention in the soil layer which is affected by cultivation is crucial to the success of the crop. The microclimate may also play a role. Extra care must be taken not to damage the roots with cultivation.

Maize can be grown on a wide range of soils, but it is important to understand that yields will vary depending on the quality of the soils. The highest maize yields are achieved on soils that have beneficial physical and chemical properties, especially well-regulated nutrient and pH balance and relatively high retention capacities. Lower yields are obtained on poorer (lighter) soils and soils with that are deficient with regard to chemical, physical and biological properties. The main factor limiting maize yield potential on poorer soils is periodic water shortages. Any soil where maize is grown should have a good structure, warm up easily in spring and have a good air circulation, while its permanent structure and abundance of organic matter should improve soil water retention. Such conditions are met by soils maintained in good condition, made up of silt, silty clay loams or sandy loams and loamy silty sand. In accordance with Polish soil suitability complexes classification these soils are the best for growing wheat and rye. Maize grows very well on loess, chernozem and black soils. It is possible to grow maize on peaty soils formed from low peats, where other cereals often do not succeed as well as maize. Corn does not tolerate cold, excessively compacted and moist soils that are hard to warm up in spring, especially heavy soils with degraded structure. It should also not be grown on soils that are too light and have poor soil moisture properties, since they dry out easily. If the soil is classified within a poorer soil complex, its quality should be improved by using organic manures rich in organic matter and natural fertilisers, and by planting maize directly after these inputs. The pH of a maize field should also be regulated, as this is a prerequisite for good development of the root system and consequently better water and nutrient uptake, lush plant growth and stress resistance. The optimum pH for maize is close to alkaline. If the pH drops below 5, maize growth is disrupted and yield can be significantly reduced.

The plant has high nutritional requirements, sometimes even comparable to those of sugar beet - for this reason maize is classified as an intensive crop. This is, of course, associated with the production of high grain and green matter yields and the relatively poor ability to take up nutrients from sources that are more difficult to access.

REGENERATIVE FARMING TECHNOLOGY

3

Location and forecrop

3.1

In regenerative agriculture, it is important to consider when the main crop is to be grown in the context of the crop rotation. What matters is not only the forecrop, but also what conditions it creates for the succeeding crop. The rotation should include crops that improve the generally understood soil fertility and phytosanitary conditions. This is particularly important when crop rotations are being simplified and when certain crops deteriorate the soil for various reasons.

Maize is considered to be a crop that does not significant requirements in terms of forecrops. Due to organisational and economic reasons, it is sometimes grown in monoculture, often without significant yield decreases being observed in subsequent years. In regenerative maize production, monocultures are not practised, so maize should always be grown in rotation with other crops.

There are many arguments in favour of growing maize in rotation with other crops. Growing the same crop species in a field for several seasons leads to the depletion of specific nutrients from the soil and causes an imbalance, as well as unfavourable changes in the soil microflora. Another problem is the accumulation of root exudates (negative allelopathy) and plant residues in the soil, which increases the pressure of pathogens and pests for which the plant grown in monoculture is a host. As a result, plants may require increased chemical protection.

A negative effect of maize farming is also its adverse effect on the soil organic matter balance (particularly maize grown for silage) and soil structure - for this reason it should be grown in rotation with plants that improve this balance and the physical properties of soils (Fig. 8).

Figure 8. The low amount of residues after harvesting maize cultivated for silage, as well as the scarce soil cover during maize vegetation and the destruction of the soil structure during harvesting are extremely detrimental to the soil organic matter balance.
Photo by A. Perzanowska

Additionally, due to the late harvesting of both grain and silage maize, its cultivation in monoculture excludes the possibility of introducing stubble intercrop mixes and winter intercrops both of which are highly desirable crops for regenerative management. Successful crop rotations enriched with intercrop mixes ensure that there is a greater variety of quality root systems and plant residues supplied to the soil, which has a positive effect on the abundance and biodiversity of soil life, from relatively large organisms such as earthworms to microscopic fungi and soil bacteria. Various crops grown with the main crop and intercrops have different growing seasons, provide different amounts of shade to the soil and affect the canopy microclimate. They also form different root masses and leave crop residues of varying quantity and quality - which is why their purposeful rotation is the basis of regenerative agriculture and aims to improve soil fertility in the broadest sense.

Selecting suitable forecrops for maize is related to the soil productivity class - as soil quality decreases, the requirements for the forecrop increase and the options for selecting forecrop species change. If soils are good, maize can be grown after cereal crops, such as wheat, barley or triticale, winter oilseed rape and more demanding broad bean crops such as pea, soybean, field bean, red clover, alsike clover, Persian clover, hybrid alfalfa and common vetch. On the other hand, maize does poorly when sown after sugar beet, which has been harvested with heavy mechanical equipment often under unfavourable moisture conditions, resulting in the destruction of the structure of the crop layer and the compaction of even deeper soil layers. When maize is planted on lighter soils, it is a good idea to introduce it after root vegetables (potato) grown on manure, and especially after small-seeded legumes (especially ornithopus) and their mixes with grasses and legumes (forage peas, yellow and narrow-leaved lupins, winter vetch) or cereal-legume mixes. Maize can also be planted after oats. On poor soils, maize should be grown as the first crop after manure application.

If maize is sown after a relatively early harvested forecrop, it should absolutely be grown after a catch crop. Regenerative agriculture makes use of the various effects of catch crops on the soil environment and the succeeding crop. Introducing them into the rotation seeks to increase the quantity and quality of organic matter in the soil, improve the physical properties of the soil (especially structure and water retention), supply atmospheric nitrogen into the soil, reduce the uptake of mineral nitrogen and other components that could be washed out of the soil, transfer nutrients from deeper layers to the surface layers of the soil, protect the soil from erosion, interrupt the life cycles of pathogens (phytosanitary properties) and suppress weeds. A catch crop's biomass can be also used to supplement the farm's roughage supply through the production of green forage and silage from the biomass, as well as autumn and early spring mob grazing of cattle on a catch crop with a suitable range of species. Roughage from catch crops can be a valuable addition to the forage especially on farms with poor quality permanent grassland.

There are multiple options when it comes to the rotation of forecrop, catch crop, and maize. Following an early harvested forecrop (end of July - first half of August), it is recommended to grow a mix of different species in a stubble. If the maize forecrop is a cereal or other early harvested crop which can be interseeded with small-seeded broad bean plants and their mixes with grasses, then the time before the planting of maize is also a good opportunity to use such an interseeding until late autumn (Fig. 9) and to provide maize with organic residues rich in nitrogen. On lighter soils, ornithopus sown into a cereal crop, such as winter rye, makes an excellent catch crop, and on heavier soils, it can be red clover sown into spring barley or other cereals, especially those grown for green forage. Both stubble catch crops and interseeded companion crops can be used for grazing or as a source of green fodder or green manure. The presence of broad bean species improves the nutritional and fertilising role of the residues. The introduction of small-seeded beans into the maize rotation is also very important in maintaining stable soil structure and biological activity. Corn can be sown also after the first cutting of alfalfa which is to be terminated.

Figure 9. Red clover as an undersown crop with cereals helps to maintain a stable structure in rotations with maize and, during wet years, can produce relatively high yields of green fodder in the autumn.
Photo by A. Perzanowska

As a warm-season spring crop with a late sowing date (end of April-early May), maize can also be grown after typical winter intercrops, especially for silage production. Most often, maize is grown after winter rye cultivated for silage or a mix of rye and winter vetch for green forage to be fed directly or ensiled with additives to improve the carbohydrate balance in the ensiled biomass. In temperate climates, winter rye is considered to be a very good species for a winter intercrop, as it has low heat requirements and resumes vegetation in early spring, significantly ahead of permanent grassland. In addition, rye grown as a winter intercrop before spring crops that required late sowing, such as maize, is a very good cover crop in fields located in hilly terrain. Covering such fields with rye in the period of autumn-winter-spring significantly reduces erosion, nutrient leaching and helps to consolidate the soil structure in rotation with maize (Fig. 10).

Figure 10. The use of winter catch crops providing a dense ground cover in autumn, winter and spring is particularly recommended for maize cultivation in hilly areas.
Photo by A. Perzanowska

It is best to sow rye for green fodder at a higher density (increasing the sowing norm by 10-20%) and slightly earlier than when cultivating this crop for grain as the main crop. Considering the conditions in central Poland, rye as a catch crop is therefore sown from 5 to 15 September, and rye/winter vetch mixes are sown as early as the end of August. Rye can be used for grazing as early as the second half of April, when the plants reach a height of 15-20 cm. At this time of the year, green forage from typical grass pastures is not yet available in such quantity. Harvesting rye for silage should be done later, at the beginning ear development (Figs. 11, 12). Silage production in a system including rye (as a winter intercrop) and maize (as a second crop) works especially well on poorer soils due to the yield reliability of winter rye. Additionally, the faster warming up of lighter soils in spring means that rye quickly produces higher green matter mass in spring under such conditions compared to its cultivation on heavier soils. A good addition to the forage base is also the cultivation of a mixture known in Poland as the Gorzow mixture as a winter intercrop before maize, which includes species such as Italian ryegrass and the bean species such as crimson clover and winter vetch. This mixture can be sown on every soil class, though an admixture of winter rye is recommended on the poorest soils (Fig. 13). Maize can also be grown after a winter intercrop of rape and agrimony, especially on better soils.

Figure 11. Harvesting rye grown as a winter intercrop for silage is an excellent and inexpensive addition to the cattle feed base, especially on lighter soils. Manure can be added in autumn when rye is to be sown or in spring with maize, after the rye has been harvested.
Photo by A. Perzanowska

Figure 12. Harvest of rye for silage in the first decade of May - growing rye as a winter intercrop before maize is a source of forage and protects soil from erosion in autumn and spring. *Photo by A. Perzanowska*

Figure 13. Gorzow mixture in the first decade of May. *Photo by A. Perzanowska*

The harvesting of maize for both grain and silage takes place late enough to prevent the timely sowing of most winter crops and intercrops after maize.

However, maize, like cereals, can be a nurse crop for interseeded plants, which has also been tested under European conditions in recent years. Grasses such as Italian ryegrass and fabaceous plants such as red clover, Persian clover, Alexandrian clover, Balansa clover or vetch, as well as mixes of grasses and fabaceous plants can be sown into interrows on a maize field. Undersowing is best done with special high-clearance seeders when the maize is at least at the four-leaf stage, which minimises the competitive effect of the undersown plants on the maize and their negative impact on the maize yield. The incorporation of intercrops into maize in regenerative agriculture is a strategy aimed at making better use of intercrops to protect the soil surface from erosion, improve the organic matter balance and the nutrient use efficiency in rotation with maize. After maize is harvested, the green forage of the undersown plants can be used for fodder and green manure, which, if intersown with legumes, can provide nitrogen for the next crop in the rotation.

In regenerative management, maize is usually followed by spring crops, for which maize should pose no risk in terms of disease transmission or pest pressure. Among cereals which can be sown after maize, oats or oat-based spring cereal mixes can be grown successfully. All fabaceous plants can also be grown after maize, if they are well selected for the soil complexes. All fabaceous plants can also be grown after maize, if they are well selected for the soil complexes. Better soils can be used for growing soybeans, field beans, spring vetch and edible varieties of white-flowered peas after maize, while lighter soils are suitable for growing field peas (pisum arvense), yellow and narrow-leaved lupins, winter vetch and mixtures of these (Fig. 14). Other plants that can be introduced into fields after maize are grasses and mixes of grasses with small-seeded legumes. Maize, in particular when grown directly after the application of manure, is a good forecrop for most spring crops. A restriction with regard to the sowing of fabaceous plants and spring cereals (especially barley) can be the use of increased doses of triazine herbicides in maize, especially if droughts occur during the maize growing season.

Figure 14. Growin different varieties of peas (for forage and human consumption) and lupins after maize is a recommended practice in regenerative agriculture.
Photo by A. Perzanowska

From the point of view of agriscience, it is possible to sow late winter wheat or spring wheat with increased frost resistance (winter varieties) after maize grown for grain and silage. However, in a regenerative approach to crop rotation, wheat should be avoided after maize. This is due to the high risk of the wheat crop becoming infected with fungal diseases caused by *Fusarium* fungi.

Also, introducing sugar beet after maize is a risk if maize has been treated with herbicides that can adversely affect beet growth (sulfonylurea herbicides). The risk of residues affecting the succeeding crop is increased, especially in the case of droughts occurring during maize cultivation season. If root crops are to be grown after maize, it is recommended to break up the residues well and incorporate them into the soil, adding a small dose of nitrogen or products to speed up the biological decomposition of straw and residues of active substances from chemical inputs, especially in soils with lower biological activity. Growing maize in rotation with a root crop, which means two crops that have a very negative impact on soil structure, requires planning the rotation to include catch crops or main crops that help improve soil structure to ensure the balance of organic matter and to simplify farming.

Choosing maize varieties 3.2

Dynamic progress in breeding has contributed to an increase in the economic importance of maize in Europe and its cultivation area over the last few decades. The genetic factor, namely the ability to choose the right variety, determines 30% of the maize yield.

The criteria for selecting varieties for cultivation differ depending on the intended use. Grain varieties should provide a high grain yield at 14% moisture content, high resistance to lodging, resistance to stem and cob fusariosis, an adequate grain to cob weight ratio and an appropriate earliness. From a practical point of view, another important feature in grain maize cultivation is the the plant's ability to remain green in the field while the grain is actively drying (stay green effect). When selecting varieties for silage, what matters most is the dry matter yield of stalks, leaves and cobs, the proportion of cobs in the total dry matter yield, the ability of the plant to keep the leaves green (stay green effect) at maturity, high digestibility (including vegetative parts). In addition, varieties are divided by kernel type into flint and dent varieties. Flint variety grains are more spherical and have a thick layer of vitreous endosperm. They have lower temperature requirements at sowing time, so can be sown earlier, in soil that is not as warm. They tend to have rapid initial vigour, which means they can survive a period of cooler temperatures in spring. The structure of the kernels makes it more difficult for these varieties to lose water content as they mature, so there can be problems with a prolonged harvest date. Dent varieties have an elongated shape and a characteristic dent at the top of the kernel, contain a higher proportion of mealy endosperm and transpire water more readily at maturity. Dent varieties have a higher yield potential and provide an abundant biomass and are very suitable for silage production. They have higher thermal requirements in the early stages of development, and if sown too early into soil that is not warm enough, they grow very slowly. The soil temperature should be 10-12 °C.

In order to fully benefit from the yield potential of the varieties, it is necessary to ensure that the plants have optimal conditions for growth and development by selecting varieties to suit the climate and soil conditions. To achieve this, close attention should be paid to the FAO number, which is an indicator of the earliness of the varieties. The first digit of the FAO number indicates the basic earliness class, while the second digit indicates the earliness group (within the basic class). The third digit describes the colour of the kernel.

According to the current classification, maize varieties are divided as follows:

– early varieties - FAO up to 230,
– medium-early varieties - FAO 240-250,
– medium-late varieties - FAO 260-290.

In Poland, this division is more detailed and varieties are split into the following earliness groups:

– very early varieties - FAO up to 190,
– early varieties - FAO 200-230,
– medium-early varieties - FAO 240-250,
– medium-late varieties - FAO 260-290,
– late varieties - FAO from 300 and above.

FAO classification is directly related to the sum of effective temperatures required to reach maturity, which also varies depending on what the maize is used for (Table 2).

Table 2. Sums of effective temperatures for maize according to FAO classification and intended use

FAO classification and maize use	The sum of effective temperatures
FAO 210 grain	1370
FAO 210 CCM	1310
FAO 230 grain	1395
FAO 240 grain	1410
FAO 240 CCM	1350
FAO 240 silage	1200
FAO 260 grain	1435
FAO 270 grain	1450
FAO 270 CCM	1380
FAO 270 silage	1240
FAO 290 grain	1480
FAO 300 CCM	1420
FAO 300 silage	1300
FAO 340 silage	1380

Source: http://www.ipm.iung.pulawy.pl/Text/Mais_probtxt.asp?lang=1

The FAO number for grain varieties is also correlated with the moisture content of the grain at harvest, and for silage varieties with the dry matter content of the whole plant at harvest.

In the face of climate change, trends in maize breeding have been changing in recent years. The most difficult task for breeders is to develop varieties that can cope with prolonged periods of drought. On the other hand, the plants need to be able to tolerate spring cold weather. Resistance breeding associated with disease pressure (cob and stem fusariosis) and pest pressure (mainly European corn borer) is becoming increasingly important. Problems with the prolonged vegetation period and harvesting under unfavourable weather conditions have resulted in the search for varieties with high resistance to lodging. Also, quick drying of grain in the cobs is very important, as it speeds up harvesting and reduces drying costs. Dry-down varieties characterised by fast drying rates have been developed in response to these problems.

Soil cultivation 3.3

The conventional approach to growing maize includes deep pre-winter ploughing as the primary tillage operation. On livestock farms, deep tillage is used in combination with an autumn application of manure. In the regenerative approach to cultivation, autumn soil management and preparation for maize sowing should be simplified as much as possible, with tillage being omitted.

Reducing the intensity of soil loosening and, in particular, eliminating inversion tillage, such as ploughing, which completely deprives the soil surface of crop residues (Fig. 15), is a method of properly managing crop residues. What happens to the residues of the previous crop has a very significant effect on the soil and on the conditions under which the succeeding crop, maize, will grow.

Figure 15. In regenerative maize cultivation, crop residues should be present on the soil surface. The use of inversion tillage, such as ploughing, deprives the soil surface of the protective function of crop residues.
Photo by A. Perzanowska

Proper management of the soil cultivation and residues of all crops in the rotation, is key to building the quality, health and resilience of arable land. Scientific research and the experience of individual farmers shows that partial incorporation into the surface soil layer or retaining all plant residues on the surface is better than removing them completely from the field surface (which is done by ploughing). This is due to a number of reasons and challenges facing modern agriculture. As farming conditions are changing (changing climate, weather extremes, declining quality and deterioration of soil caused by intensive conventional tillage, fluctuating prices for raw materials and services) with respect to past decades, the objectives of cultivation are also changing to:

- improve soil water retention and unproductive soil water loss;

- limit soil organic matter loss and improve soil organic carbon sequestration;

- improve the biological activity of the soil;

- reduce the occurrence of water and wind erosion;

- limit the degradation of soil structure;

- reduce runoff and leaching of fertiliser components;

- reduce cultivation costs, labour time and energy consumption.

Ploughing is a very costly operation which requires a lot of energy. It also destroys and disturbs the natural structure of the soil. Soil with an unstable and damaged structure loses organic matter more quickly and becomes compacted more easily. As the stability of the soil structure degrades and the organic matter content decreases, other physical, chemical and biological properties of the soil also deteriorate. Soils with poor structure and low organic matter content exhibit poor properties when it comes to water retention and air circulation, have a less stable water and air transmission pore network and a poorer ability to absorb rainwater. They easily become eroded and crusted, and are less biologically active. Ploughing is followed by a sequence of further interventions to prepare the field for seed planting, since in this cultivation system it is necessary to carry out a series of soil conditioning treatments before sowing, which adversely affects the natural soil structure and increases cultivation costs. Apart from crusting, conventional ploughing carried out over many years is associated with other soil problems, such as hardpan layer subsoil compaction. Maize reacts to the presence of a hardpan layer and subsoil compaction with impaired growth. As research has shown, the presence of compacted subsoil beneath the cultivated layer results in poorer development of the root system and its reduced reach. With compacted soil and weaker root system development, maize takes up nutrients and water less efficiently and is more susceptible to moisture deficiencies, ultimately resulting in reduced yields.

If there is a suspected hardpan or subsoil compaction in the field (plants in such zones of the field grow poorly and there are problems with rainwater absorption - Fig. 16), it is essential to carry out subsoiling or deep plowless cultivation in the zones of the field affected by such problems. Subsoiling is best carried out when soil moisture is relatively low, preferably immediately after harvesting the forecrops. Also, when transitioning to regenerative farming with reduced tillage in fields that have been ploughed for many years, the first step should be to restore the functionality of the deeper soil layers by deep loosening or deep reduced cultivation.

Figure 16. If there is a suspicion of a hardpan or subsoil compaction in the field, subsoiling is an absolute must.
Photo by A. Perzanowska

In regenerative maize production, based on reduced tillage systems, problems with the soil problems described above are diminished. Replacing ploughing with simplified cultivation systems, combined with the use of a well-planned crop rotation and appropriate residue management, keep the different soil layers physically and biologically healthy and results in satisfactory yields. Such planning is crucial, as in crop rotation where maize is the primary crop, there is a significant need to improve the affected soil structure and support biological life that is impacted by wide-row cultivation. Growing crops in wide rows without the presence of forecrop residues on the field surface exposes the soil to erosion and greater fluctuations in temperature and moisture, compared to growing crops in narrow rows. With reduced maize soil cultivation system, one can quickly notice increased earthworm activity in the field throughout the cultivated layer (Fig. 17 and Fig. 18) from early spring and practically until the first frosts. Earthworm casts, which are a mixture of soil and organic matter, are at the same time very stable aggregates of biological origin and play a key role in the formation of a stable structure in cultivated soils. If the soil is largely made up of such stable soil aggregates, then soil porosity, water infiltration and retention are improved, and the susceptibility of the cultivated soil to soil crusting or compaction is reduced. Combining reduced tillage with the incorporation of crop residues, including post-harvest maize straw in the case of maize grown for grain, encourages earthworms to „work", thus helping to increase the resilience of arable fields to changing weather conditions, exacerbated in recent decades by increasing climate change. It also leads to a natural, biological loosening of the soil structure and makes the soil crumbly, which makes mechanical tillage much easier and more effective.

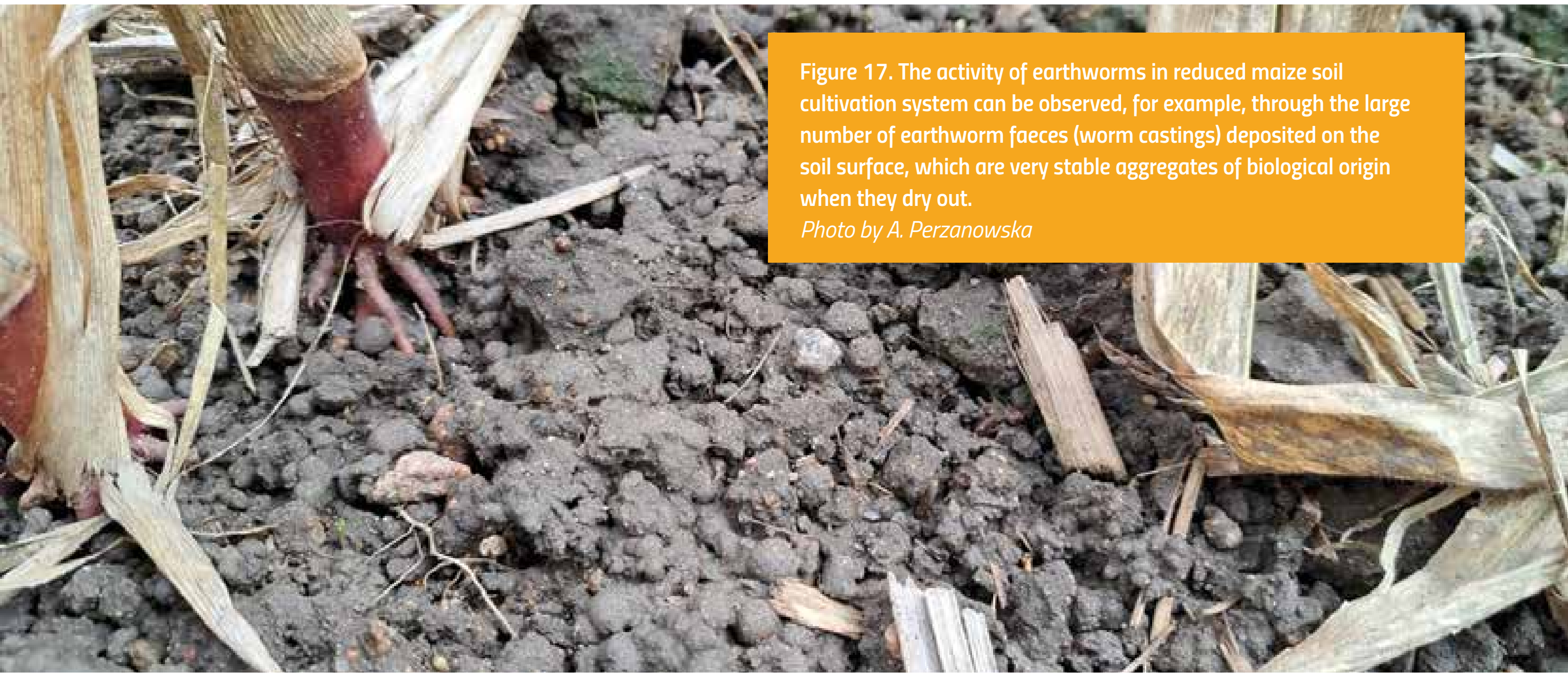

Figure 17. The activity of earthworms in reduced maize soil cultivation system can be observed, for example, through the large number of earthworm faeces (worm castings) deposited on the soil surface, which are very stable aggregates of biological origin when they dry out.
Photo by A. Perzanowska

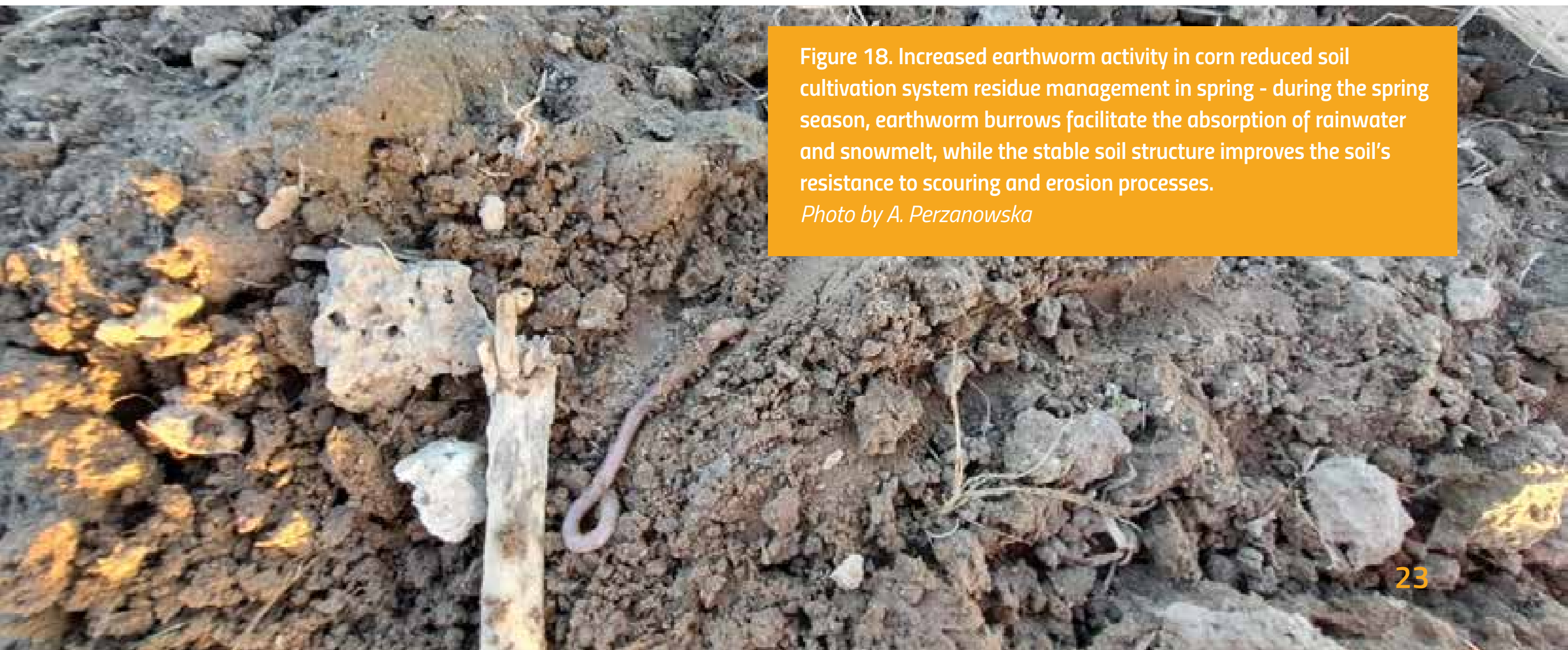

Figure 18. Increased earthworm activity in corn reduced soil cultivation system residue management in spring - during the spring season, earthworm burrows facilitate the absorption of rainwater and snowmelt, while the stable soil structure improves the soil's resistance to scouring and erosion processes.
Photo by A. Perzanowska

When using a reduced tillage system on fields, cultivation is carried at different depths. It requires agricultural machinery with different working units having various types of cultivator tines, disc harrows, coulter harrows, spring harrows and rotary harrows. Cultivation can be deep and shallow, or limited to surface only. The sequence of cultivation treatments in reduced technology can be as follows: shallow cultivation immediately after harvesting the forecrop - medium or deep reduced tillage as the primary method of cultivation replacing ploughing followed by plant sowing.

Shallow reduced surface soil cultivation immediately after harvesting a forecrop can successfully replace traditional stubble cultivation carried out with a plough. A shallow post-harvest cultivation is carried out in order to disrupt and break up the sections of the capillaries that are in direct contact with the atmospheric air. Thanks to this intervention, unproductive evaporation from the surface layer of exposed soil after harvest is significantly reduced, especially if there is little post-harvest residue left to act as a protective layer against moisture loss. Rapid loosening of the surface layer of soil also stimulates weed and forecrop seeds to germinate quickly - such seedlings can be easily destroyed mechanically with another shallow loosening operation and thus replace the chemical method of weed control with shallow soil ripping.

If the straw from the forecrop and the straw after the grain maize harvest is managed in the field, it should be well shredded and evenly spread over the field before mechanical cultivation (Fig. 19). Stubble cultivation after harvesting a forecrop intended to work straw and crop residues into the soil should be appropriate to the yield of the straw which is to enrich the soil so as to create optimum conditions in the soil for its mineralisation - for every tonne of residue left, the depth of cultivation should be a minimum of 2 cm. According to this general rule, if a straw yield of 5 tonnes is expected, then effective incorporation of straw into the soil can be achieved by cultivating to a depth of at least 10 cm. This rule also applies to straw from other crops.

Figure 19. Straw from maize and other crops rotated with maize should be well shredded and evenly distributed over the field surface before stubble cultivation.
Photo by A. Perzanowska

Shallow stubble cultivation can be combined with sowing intercrop mix. The success of stubble intercrops is determined by the timing of their sowing - the sooner the better. It is recommended to leave the biomass of the intercrops on the surface for the winter. The same applies to straw and forecrop residues shredded and evenly distributed in the stubble, or incorporated into the surface layer. In the case of spring intercrops sown into stubble, their biomass will die back in autumn and winter. This biomass cover effectively protects the soil surface from water and wind erosion, as well as moisture loss, and stimulates biological life in the soil from the surface down to the deeper layers. Stubble intercrops should not be allowed to produce seed before winter - this is especially important in the case of white mustard and phacelia sown directly after early terminated forecrops.

Winter intercrops also play an important role in protecting the soil and can be used as green manure or fodder before maize sowing. If a winter intercrop is to be sown before maize, the seeds should be sown in a properly prepared soil. In such cases, the same soil preparation rules apply as for reduced cultivation of winter crops grown as the main crop. When intercropping winter rye or its mixture with winter vetch, which usually takes place in the first half of September, the period between harvesting the forecrop and sowing the rye should be used for mechanical weed control. To accomplish this, shallow cultivation is performed after the emergence of weed seedlings to mechanically destroy them. If maize is sown after a winter rape intercrop, mechanical post-harvest weed control is limited due to the early sowing of rape (up to 20 August). Winter rape intercrops can be terminated in spring using a reduced mechanical method without the need for chemical treatments. In such a case, passive tillage tools (disc harrows, kernel processor rolls and knife rollers, cultivators) as well as active tillage tools (rotary tillers, rotary harrows) are used. The key condition for successfully destroying such crops is a good undercutting of the intercrop roots, or effective near-surface breaking and crushing of the plant above the ground, effectively destroying the assimilation apparatus and disabling plant regrowth.

The next stage in reduced maize cultivation involves practices carried out in spring before sowing takes place. These practices vary depending on the sowing method. The options include precision seeding of corn seeds after working crop residues into the soil, seeding directly into mulch from crop residues on the field surface without tillage (so-called direct seeding, no-till) or strip seeding into crop residues, including winter intercrop residues (Fig. 20). Strip seeding can be done into residues from a forecrop that has been incorporated shallowly into the soil beforehand, or straight into the residues without any cultivation beforehand.

Figure 20. Strip seeding of maize into the residue of a winter oilseed rape intercrop that had been sown using the reduced method and destroyed using a knife roller at the end of April. *Photo by A. Perzanowska*

Successful management of forecrop residues and intercrops improves the stability of the soil surface layer, which, without the protective function of plant residues, is easily exposed to factors that damage the soil structure, such as rainfall or wind, especially in autumn, winter and spring. Without cover, the soil also loses water easily and dries out, which becomes particularly evident during periods with low rainfall. The surface layer of the soil which has unstable structure becomes easily affected by rain and after drying out it forms a hard crust. The crust makes gas exchange between the soil and the atmosphere and plant emergence more difficult and increases the risk of disease infestation, as well as exacerbating the drying out of the surface layer of the soil (Fig. 21 and 22).

Figure 21. Leaving maize residues on the soil surface for the autumn and winter is a far better choice than ploughing them in.
Photo by A. Perzanowska

Figure 22. In till farming systems the loss of soil structure stability and soil crusting is more common, as the structure-forming and protective role of crop residues is completely disregarded.
Photo by A. Perzanowska

As already noted, maize can tolerate far simpler cultivation. However, a limitation to the no-till approach, especially when direct sowing with full mulch on the soil surface and strip sowing directly into the mulch from the previous crop, may be the slower warming up of the soil in spring. In temperate climates, this can have a detrimental effect on the rate of germination and emergence of thermophilic maize. The type of mulch, as well as the cover crop species used, also play a role (Fig. 23). It may be even more significant if the soil is heavy, the field lies low or becomes waterlogged, and warms up more slowly in spring, compared to lighter soils or soils situated, for example, on well-lit south-facing hillsides Compared to lighter soils or soils situated, for example, on well-lit south-facing hillsides. Hence, in such cases cultivation should not be radically simplified. Good results in maize production are achieved with zone tillage (strip-till) compared with ploughing and no-till. The advantage of this system in maize farming is that the soil in the rows with no plant residues warms up faster and the growing conditions for maize are improved. Deep fertilisation is provided, which improves the efficiency of nutrient use, while the presence of uncultivated strips covered with residues makes the whole system beneficial for absorbing rainwater and conserving soil moisture in periods of moisture shortage.

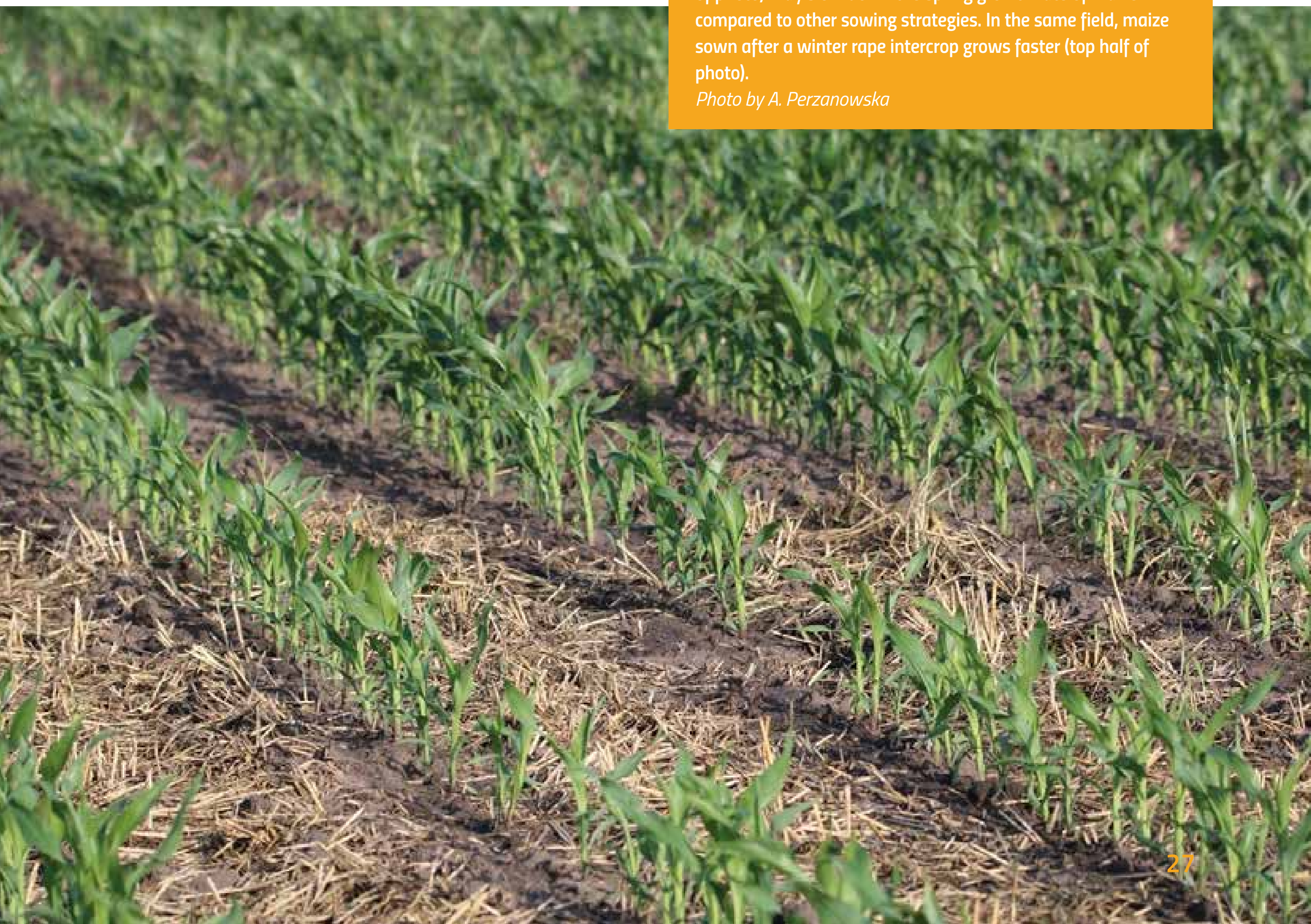

Figure 23. Sowing maize into winter rye mulch (bottom half of photo) may slow down the spring growth rate of maize compared to other sowing strategies. In the same field, maize sown after a winter rape intercrop grows faster (top half of photo).
Photo by A. Perzanowska

In the case of direct seeding, there may also be problems with plant density due to the difficult sowing conditions in the presence of a large amount of crop residues and an uneven field surface. As a result, it is more difficult to accurately plant the kernels in the soil (Figs. 24 and 25). Therefore, if direct seeding is done, it is important to use special seeders designed for no--till systems which can place seeds in the residues of the previous crop. Sowing rate can also be increased by 10-20% in order to ensure satisfactory plant density (assuming that some will not germinate). It is also recommended that direct seeding should be carried out under conditions of sufficient soil moisture to ensure good plasticity and relatively low viscosity.

Figure 24. Direct seeding into mulch from a forecrop of does not always guarantee good seed coverage in the soil - it is crucial to choose the right seeder, suitable for working among large amounts of residues and uneven soil surfaces, and to sow at optimum soil moisture conditions.
Photo by A. Perzanowska

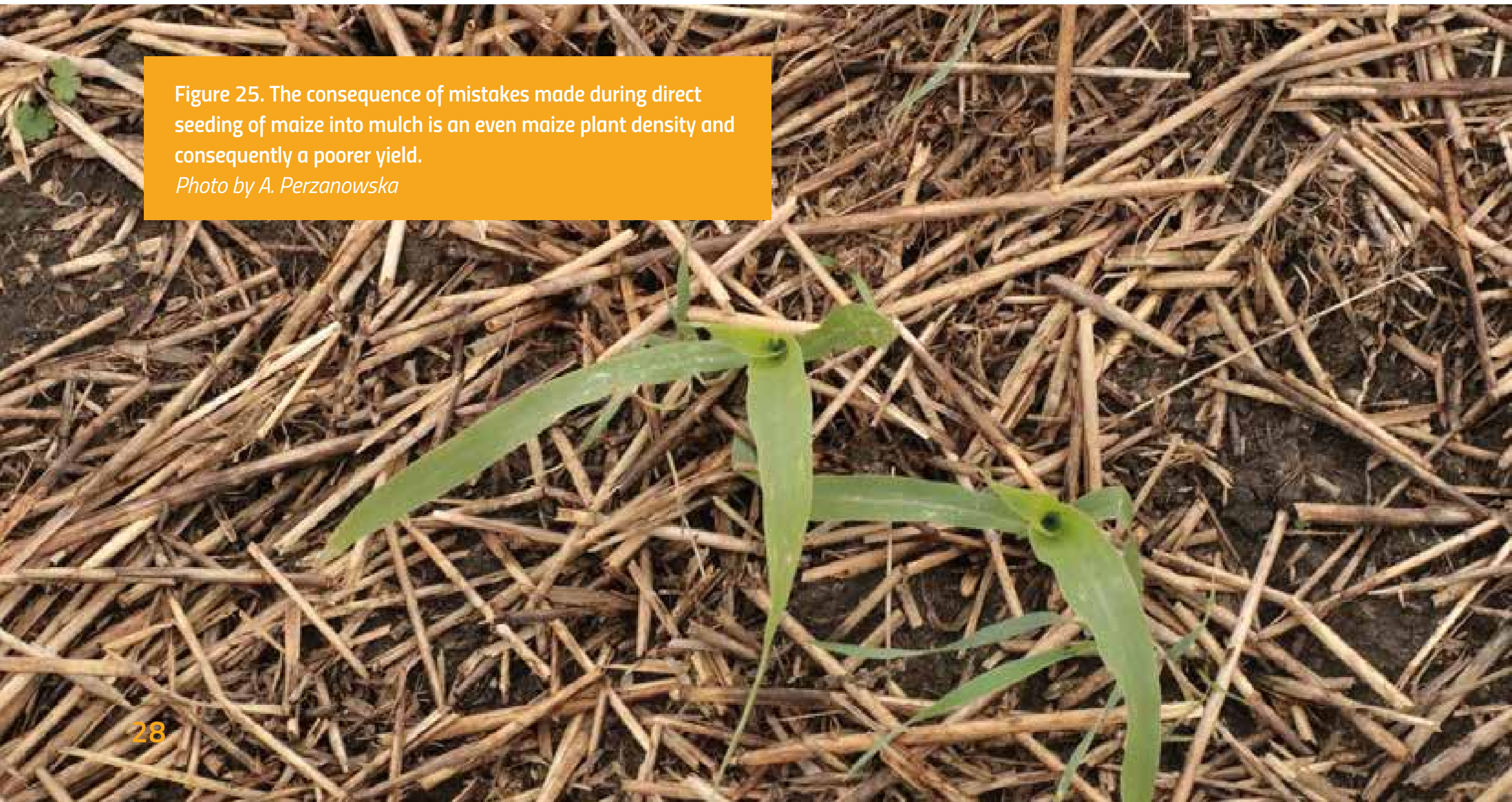

Figure 25. The consequence of mistakes made during direct seeding of maize into mulch is an even maize plant density and consequently a poorer yield.
Photo by A. Perzanowska

Any cultivation or driving of agricultural equipment in the field should be carried out at optimum moisture so as not to impair the physical quality of the soils - both the cultivated layer and the deeper soil layers. Soils that are too moist become easily compacted under pressure of the equipment, even at greater depths. Optimum soil moisture ensures the best mechanical cultivation results (the soil crumbles, rather than becomes wet or excessively clumpy and does not stick to the working elements of machinery and tillage tools) and allows for the best preparation of the cultivated layer for sowing, as well as the best quality of seeding. Where direct seeding is used in maize cultivation, driving through the field should be kept to a minimum and ideally controlled traffic should be used.

Seeding 3.4

Corn seeding should be made early enough to ensure growth in conditions of a short day and good soil moisture, which usually decreases as the spring and summer progress. On the other hand, seeds should be planted when the soil has reached the minimum germination level for maize (6°C) and when the risk of major frosts, which can fatally damage the plants, has passed. Flint varieties can tolerate earlier sowing. Maize grown for grain should not be sown too late, while early varieties show greater tolerance to delayed sowing.

The optimum sowing time for maize is usually in the 3rd decade of April and is subject to modifications depending on the region and the weather conditions of a given year, especially the risk of frost. Phenological indicators can help to determine the optimal sowing date for maize. The signal for maize seeding is the start of dandelion flowering, which generally coincides with the end of the stem elongation stage of winter cereals that quickly resume vegetation in spring, such as winter rye (Fig. 26). The optimal temperature for maize sowing coincides with the full to late flowering of eastern groundsel (Fig. 27).

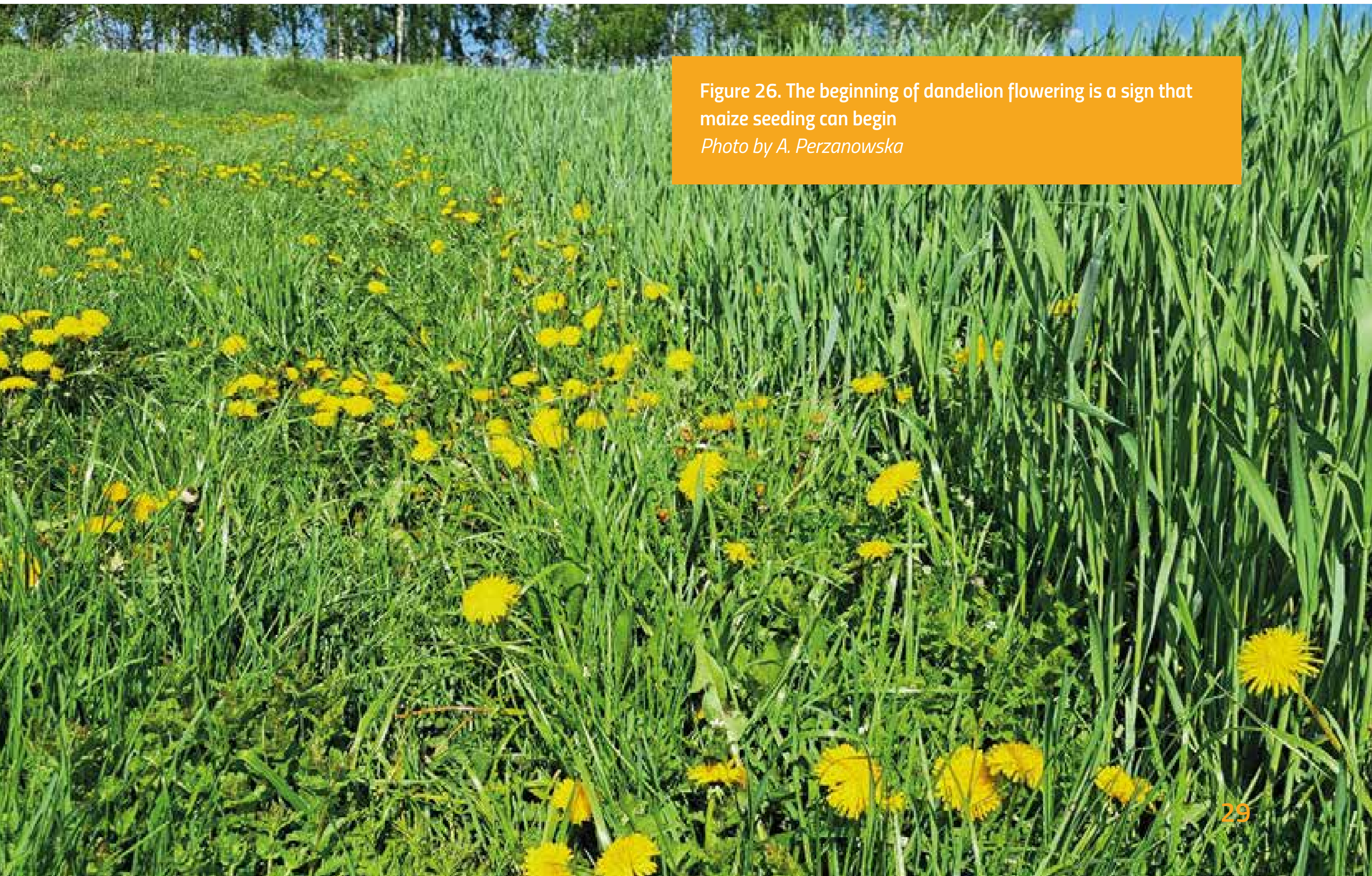

Figure 26. The beginning of dandelion flowering is a sign that maize seeding can begin
Photo by A. Perzanowska

Figure 27. A useful signal for determining the optimal period for maize sowing coincides with the full to late flowering of eastern groundsel.
Photo by A. Perzanowska

Unfortunately, there are years when spring frosts happen relatively late. If a frost occurs and the plants are damaged by sub-zero temperatures, before deciding to replant the maize crop, it is important to assess the potential of the plants to regenerate. If the growth cones have not been damaged, new leaves may be observed developing from the growth cones as early as 3-5 days after the frost. If the plants are still alive and leaf damage does not exceed 70%, it is recommended to leave the plantation to regenerate - observations have demonstrated that this is more economical than re-seeding the plants. To evaluate the condition of the plants after frost, uproot one plant, cut it lengthwise and examine whether new leaves are emerging in the cone. A dead growth cone is soft and watery. If significant frost damage is evident, maize plantations should be replanted as soon as possible.

The sowing depth of maize seed is on average 5-6 cm. Deeper sowing, which is 6-8 cm, can be done on lighter soils and other soils where there problems may occur with moisture in the surface layer of the soil during the sowing period, which may delay or even prevent emergence.

Maize is sown at a low density - since maize is a C4 crop, the sowing density should ensure that individual plants in the canopy receive good light, regardless of whether maize is grown for grain or silage. Maize sowing density and plant density should follow the recommendations for a particular variety. The recommended plant density for grain crops is 70-110,000 kernels per hectare and for silage 9-14,000 kernels per hectare, depending on the earliness and production capacity of the field. The density of maize grown for CCM should be similar to that of grown for grain and should not exceed 11 kernels per $1m^2$ - this approach makes it possible, if necessary, to abandon the CCM harvest and harvest the grain itself. On poorer soils, maize should be sown less often and the earlier varieties should be sown more densely. Currently, maize hybrid seed is sold in sowing units containing usually 50 or 80 thousand live seeds. Sowing maize for the main crop using self-produced seed is not allowed.

Precision sowing or zigzag planting is used in maize sowing. In traditional precision sowing, the seeds are placed in rows every 75 cm, with equal row spacing (every 11-16 cm). In silage maize cultivation, narrower row spacing can be adopted. The zigzag pattern consists of reducing the row spacing (to 37.5 cm) and at the same time increasing the distance between the seeds in adjacent rows (to 26.8 cm) compared to traditional precision sowing. Seeds in adjacent rows should be offset by 13.4 cm from each other. Such seed placement in adjacent rows should roughly form the sides of an isosceles triangle. Following a triangular pattern provides a larger and more circular area per plant and thus allows better use of nutrients, solar energy and soil water. In this method, the canopy becomes compact earlier compared to conventional sowing, which in turn has a beneficial effect on reducing erosion and evaporation from the soil surface and makes the maize canopy more competitive against weeds. Field trials indicate that higher yields, with better energy value, can be obtained from zigazg sowing.

Seeding should be done with care, modified to take into account the soil conditions. Precision seed drills are equipped with tools for adding fertiliser in rows, which place the pellets at a distance of about 5 cm from the seed, which significantly supports the plants in the initial growth phases.

Irrigation and water management 3.5

Given that the Earth's water resources are limited, irrigation of maize should be a last resort, although farmers are making the decision to do so more and more often due to troubling droughts. The regenerative approach advocates solutions aimed at increasing the amount of water retained in the soil, so that irrigation can be avoided. It also recommends the use of cultivation methods that are more likely to conserve soil moisture during critical periods. It is also important to select a suitable site for maize cultivation, avoiding planting maize on soils prone to excessive dryness. In order to minimise the impact of moisture deficiencies that impair maize growth, conservation techniques such as reduced tillage with forecrop residues on the soil surface, introducing intercrops as green manure, mulching soils and maintaining a positive organic matter balance should be used in maize cultivation. It is also important to manage maize cultivation in such a way as to ensure good root system development and overall plant health. This is achieved through balanced fertilisation, regulation of the soil pH and elimination of physical soil problems, such as hardpan layer and subsoil compaction, which limit the development of deep maize roots and groundwater infiltration into the rhizosphere. When irrigation is necessary, it should be applied with precision and adapted to the actual needs of the maize, taking into account critical periods.

Maize water needs, depending on the climate, range from 500 to 800 mm. As regards the use of water stored in the soil for plant growth, the range is 40% during the sowing period, 55 to 65% during the periods from leaf development to crop formation and up to 80% at maturity. Under typical soil conditions in temperate climates, the water needs of maize are met by a rainfall of 200 mm, and the maize takes the rest of its water from groundwater, soil water reserves and dew. In Poland, rainfall during June-August is particularly important and during this period 150 mm of rain should fall to secure the water needs of maize. As maize draws a significant amount of water from the soil, it is important that the groundwater level is kept relatively shallow, preferably at a depth of about 1 m.

Maize can tolerate rainfall deficiency during the initial leaf formation and maturation period. Also, when it comes to proper root development, the plants need a supply of water to the root zone from rainfall or irrigation at the time of seeding or shortly afterwards. Although in well-structured soils maize roots can reach up to a depth of 2 m and deeper, the largest part of the fully developed roots is in the soil layer up to 0.8 - 1 m. Due to this distribution of maize roots in the soil, about 80% of the water uptake from the soil takes place from this depth and the rest from deeper layers. Flowering phase in particular is a critical period for maize plants. Water shortage, especially during the pollen season, can result in a low grain yield due to a reduced pollination efficiency of the female flowers in the cob and consequently the number of kernels developing inside. On the other hand, a water deficit at the final stage of maturation has little effect on yield. Therefore, in rain is scarce and there is insufficient water supply for irrigation, irrigation planning should be based on avoiding water deficits during flowering, going as far as limiting water supply during leaf growth and grain formation, without reducing plant yield.

Maize can manage water very efficiently, but maize grain and biomass yields can be effectively controlled by well-planned irrigation in areas that require it, combined with optimal plant fertilisation. It is crucial to adapt irrigation frequency and doses to the water requirements of maize during its various development phases. In the climate of Europe and during a typical spring, when there are still winter water reserves in the soil, irrigation of maize is not practically necessary until the 10 leaf stage. In some years, severe early spring drought can make irrigation necessary so that kernel germination and plant emergence are possible at all. From the development of the 12th leaf onwards, the growth rate of maize increases considerably, which means that more water is used from the habitat. It is considered that a dosage of about 5 mm of water per day for maize in our climatic conditions allows for the full yield potential of currently available maize varieties to be utilised.

The best and most efficient method of providing water to maize plantation is drip irrigation, channelled precisely into the rhizosphere through a system that is either above or below the surface. In this type of irrigation system, water is applied at low pressure in small doses, ensuring uniform moisture distribution. It also ensures that the irrigated soil layer is not excessively damp and does not over-water the cultivated layer. Drip irrigation can be successfully combined with fertiliser application. The irrigation system should be equipped with moisture sensors and strain gauges to continuously monitor soil moisture and help make irrigation decisions based on graphs showing the current level of stored water in the soil, taking into account the field water capacity of the soil. Apart from adequate soil moisture and nutrient levels, root development and water uptake are also strongly influenced by salinity. If salinity is too high, plant uptake of water from the soil is reduced or even impossible.

3.6 Plant and soil fertilisation

Maize is a plant with significantly high nutrient requirements. Nutrient deficiencies impair the development of the roots and the parts above ground, including the cobs. Insufficient supply of specific nutrients results in less vigorous growth and a defective development of the cobs, with a significant impact on the overall yield of biomass as well as grain. Undernourished plants produce smaller, less filled cobs compared to plants that have been properly fertilised (Fig. 28).

Figure 28. Maize reacts to nutrient deficiencies by disrupted cob size, filling and shape. If there are deficiencies of nitrogen, phosphorus and potassium, the tips of the cobs are poorly filled. With not enough phosphorus, the cobs are small and bent in a characteristic way.
Photo by A. Perzanowska

According to the principles of regenerative farming, soil correctives should be added based on soil test results. In the case of plants with high nutrient requirements, such as maize, it is essential to make sure that the soil is rich enough. Fertiliser doses should also take into account the nutritional requirements of the crop that are relevant to the yield of the farm.

Natural and organic fertilisers

Maize is a crop that responds very well to manure fertilisation and, similar to root crops, can be grown with full doses of this natural fertiliser. The role of natural fertilisation cannot be overstated, especially when growing maize on lighter soils. Natural fertilisers are not only a source of nutrients, but also a source of organic matter (especially manure), which on lighter soils is largely responsible for the soil sorption capacity and reduced nutrient leaching. Manure fertilisation is of great importance, especially when maize is grown for silage - the application of a mixture of organic matter found in manure makes up for the degradation of soil organic matter caused by silage maize cultivation. It also helps to rebuild soil structure (Fig. 29).

Figure 29. Field after silage maize harvest. Manure application on fields where maize is grown for silage is a tool to reproduce soil organic matter and to help rebuild soil structure.
Photo by A. Perzanowska

The nutrient content of natural fertilisers depends on the type and form of the fertiliser. Table 3 shows the average values of selected nutrients for different types of manures. However, it should be noted that the actual composition of the fertiliser used on the farm can only be determined by analysing a sample in the laboratory.

Table 3. Average content of minerals for different types of natural manures.

Type of fertiliser	Mineral content in natural fertilisers					
	N	P_2O_5	K_2O	CaO	Mg	Na
Manure:	$kg \cdot t^{-1}$					
cattle	4,7	2,8	6,5	4,3	1,5	1,0
pigs	5,1	4,4	6,8	4,4	1,8	1,1
horses	5,4	2,9	9,0	4,3	1,6	0,6
sheep	7,5	3,8	11,9	5,8	1,9	1,2
Slurry:	$kg \cdot m^{-3}$					
cattle	3,4	2,0	3,7	2,1	0,8	-
pigs	4,3	3,3	2,3	2,8	0,8	-
Liquid manure:	$kg \cdot m^{-3}$					
cattle	3,2	0,3	8,0	0,6	0,4	-
pigs	2,8	0,4	4,1	0,8	0,3	-
Poultry dung:	$kg \cdot t^{-1}$					
hens	16	15	8	24	7	-
ducks and geese	5-10	5-14	6-9	8-16	2-3	-

Source: Own elaboration on the basis of Maćkowiak and Żebrowski, 2000, Maćkowiak, 2004, Kropisz, 1997

Plant available nutrients from natural fertilisers are released gradually. Table 4 shows the amount of nutrients released from a selection of natural fertilisers in the first year and the following year after application.

Table 4. Utilisation rates of nitrogen (N), phosphorus (P) and potassium (K) from specific types of natural fertiliser (cattle).

Type of fertiliser	Nutrient use efficiency – 1st year after the application			Nutrient use efficiency – 2nd year after the application		
	N	P	K	N	P	K
Manure	0,35* - 0,40**	0,4	0,8	0,15	0,3	0,1
Slurry	0,50*- 0,60**	0,7	0,8	0,1	0,1	0,1
Liquid manure	0,55* - 0,75**	-	0,8	-	-	0,1

*applied in autumn, **applied in spring

Source: Own elaboration on the basis of Maćkowiak, 1999; Polish Journal of Laws Dz.U. 2018 item 1339 and Polish Journal of Laws Dz.U. 2023 item 244

In the case of manure application, the well rotted manure should be incorporated into the soil immediately after being hauled. The autumn application of manure on fields where maize is to be planted provides good results. The same can be done in the case of a winter rye or winter rape catch crop. Liquid manures (slurry and liquid manure) should be injected into the soil (not splashed). Slurry should be applied during rainy weather and when temperatures are relatively low to reduce ammonia losses and odour. Following these instructions limits significantly the loss of nitrogen from fertilisers (via ammonia emissions) and its release into the environment, and also minimises the destruction of the topsoil structure. Fertiliser application must also respect the guidelines of the Nitrate Reduction Programme document, which imposes an obligation to determine the amount of residual nitrogen present in all sources before proceeding with nitrogen fertilisation. Table 5 shows the data used to calculate residual nitrogen from natural and organic fertilisers.

Table 5. Example of calculations of residual nitrogen from natural fertilisers.

Type of fertiliser	Nitrogen use efficiency [A]	Fertiliser dose [$t \cdot ha^{-1}$, $m^3 \cdot ha^{-1}$] [B]	Total nitrogen content in [$kg\ N \cdot t^{-1}$ of organic fertiliser] [C]	Amount of available nitrogen taking into account use efficiency [$kg\ N \cdot ha^{-1}$] [A·B·C]
Cattle slurry applied in the spring	0,60	20	3,4	40,8
Cattle manure applied in the autumn	0,35	25	4,7	41,1

Source: Own elaboration on the basis of Polish Journal of Laws Dz.U. 2018 item 1339 and Polish Journal of Laws Dz.U. 2023 item 244

Organic fertilisers such as composts, straw and so-called green manures, i.e. fresh plant matter introduced into the soil to increase soil fertility, are also a valuable source of nutrients and soil organic matter. If straw of cereals grown before maize is managed in the field, a compensating nitrogen dose can be applied to accelerate the decomposition of the straw. To calculate the nitrogen dose that compensates for nitrogen deficiencies in the straw, the following formula is used (Grzebisz 2009):

$$Dkn = Pno \cdot (12 - Nno)$$

whereas: Dkn – compensating dose (supplementary) of nitrogen ($kgN \cdot ha^{-1}$)
Pno – straw weight ($t \cdot ha^{-1}$)
Nno – current nitrogen content in the straw ($kgN \cdot t^{-1}$)

If maize is grown after legumes, the amount of residual nitrogen remaining after legumes must also be taken into account before proceeding with mineral nitrogen application to maize. The calculation is based on the data presented in Table 6.

Table 6. Amount of residual N after legumes and root crops.

Type of forecrop	Legumes in pure sowing		Legumes in mixed sowing with grasses or cereals		Leaves of root crops mixed with soil
	Main crop	Catch crop	Main crop	Catch crop	
Post-harvest residues mixed with soil	30 kg	15 kg	20 kg	10 kg	25 kg
Whole plants for green manure mixed with soil	Yellow lupine – 74 kg Pea – 77 kg Serradella – 65 kg Other – 60 kg	Red clover – 30 kg White clover – 27 kg Serradella – 33 kg Other – 30 kg	50 kg	20 kg	-

Source: Polish Journal of Laws Dz.U. 2018 item 1339 and Polish Journal of Laws Dz.U. 2023 item 244

Maize has a particularly high requirement when it comes to potassium, followed by nitrogen and finally phosphorus. It also has a high uptake of calcium and magnesium, as well as sulphur and micronutrients compared to staple cereals. The need for nutrients in maize plants is calculated by taking into account the fertility of the soil, the amount of natural and organic fertiliser used, and the amount of nutrients extracted per tonne of crop (Table 7). Additionally, the expected yield of maize given the soil conditions in a specific field is taken into consideration in the context of the mineral fertiliser applied in a specific dose. In the regenerative production of maize, the nutritional needs of the plant are estimated, and these should be met with an appropriate dose of mineral fertiliser. It is absolutely essential to remember that the effectiveness of fertilisation of this plant, which is sensitive to low soil pH, depends on the acidity of the soil.

Table 7. Average macronutrient and micronutrient uptake in maize per 1 tonne of main crop with the corresponding and amount of by-product (grain crop)

Plant	Macronutrients [kg]						Micronutrients [g]			
	N	P	K	Mg	Ca	S	B	Cu	Mn	Zn
Grain maize	26	5,4	23,2	5,7	6,7	6,6	11	14	107	85
Silage maize	4	1,3-1,5	6,3-7,7	0,7-0,9						

Source: IUNG; Kruczek and Książak (2004)

In regenerative maize cultivation, it is recommended to apply fertiliser locally at various depths. When aerating the soil during reduced cultivation, mineral fertilisers should be applied to a depth of 15-30 cm (deep fertilisation) and during sowing to a depth of 5-10 cm (shallow fertilisation, also known as under-root fertilisation next to the kernel and deeper). Deep fertilisation makes the plants utilise the fertiliser nutrients more efficiently and develop a deeper root system, which strengthens their ability to withstand environmental stresses, especially drought.

Nitrogen fertilisation

Nitrogen is the most important nutrient in terms of yield and its application has the greatest effect on increasing yield weight and quality. This effect of nitrogen declines as other macronutrients and micronutrients are depleted from the soil. Therefore, the effectiveness of nitrogen fertilisation is also determined by a balanced fertilisation of the other nutrients, ensuring their proper balance in the soil.

Maize takes up large amounts of nitrogen throughout the growing season. For maize grown for grain, the average total nitrogen application is 180-200 kg N per hectare at a yield level of 9-10 tonnes of grain per hectare. In silage maize cultivation, an average of 190-220 kg N per hectare is applied with an assumed green fodder yield of 80 - 100 tonnes per hectare. On better soils, full nitrogen dose may be applied directly before sowing maize, and in this case slow-release nitrogen fertilisers such as urea, nitrate fertiliser or ammonium sulphate (alkaline soils) should be used. On lighter soils, it is recommended to apply 30-50% of the nitrogen dose before seeding, while the remainder should be applied during leaf development phase, when it is still possible to operate the fertiliser spreader over the growing crop. In this case, quicke-release fertilisers such as ammonium nitrate, calcium ammonium nitrate or UAN are used. When applying nitrate at the leaf development stage, it is important to be careful not to burn' the plants, which occurs when the fertiliser granules are trapped on leaf collars and dissolve in rainwater or dew, and the concentrated fertiliser solution damages adjacent tissues. Spreading fertiliser should therefore be carried out on a dry day and using spreaders equipped with in-row fertiliser applicators. A good solution for top dressing in regenerative maize cultivation, aimed at ensuring plant health and vigour, is the use of UAN in combination with a nitrogen stabiliser. UAN can be applied as a late top dressing twice - at the 2-5 leaf and the 6-10 leaf stage.

When determining specific mineral nitrogen doses, it is necessary to take into account the amount of active nitrogen from different sources. The total amount of nitrogen available from all sources (Nd) for maize production depends on the agronomic category of the soil: on heavy and medium soils it is 240 kg N·ha^{-1}, on light soils it is 216 kg·ha^{-1}, and on very light soils it is 192 kg·ha^{-1}. To calculate the maximum dose of nitrogen to be provided with fertilisers, it is necessary to take into consideration the amount of mineral nitrogen present in the soil in spring and the nitrogen use efficiency from mineral fertilisers (0.7). If manure or other natural fertilisers are applied, including organic fertilisers, the amount of residual nitrogen from these fertilisers must also be taken into account when determining the mineral nitrogen dose (Tables 3 to 6). If natural and organic fertilisers are not used, the calculation of Nd is limited only by the Nd present in the soil in spring and the mineral fertiliser use efficiency.

Fertilisation with nitrogen should be carried out carefully, appropriate to the soil conditions and the needs of the plant. Over-fertilisation with nitrogen can lead to an accumulation of nitrates and nitrites in the plant which causes excessive hydration of plant tissues and makes them more susceptible to low temperatures, pests and diseases. Furthermore, when consumed by people or animals, they have a detrimental effect on health. Excessive nitrogen concentrations in the soil also have a negative effect on the soil biological properties. If nitrogen is not absorbed by crops, it is released into the environment in the form of nitrous oxide (a very potent greenhouse gas) and contaminates groundwater and surface water. Inefficient nitrogen management also primarily results in financial losses for the farmer. Sustainable, regenerative crop production should follow the guidelines of the Programme of measures to reduce water pollution by nitrates from agricultural sources and to prevent further pollution which entails carrying out nitrogen fertilisation plans, monitoring nitrogen levels in the soil and not exceeding the maximum nitrogen application doses from all sources of nitrogen for maize.

Phosphorous fertilisation

Phosphorus plays an important part in energy conversion processes. With correct fertilisation with phosphorus, maize plants manage water and carry out photosynthesis more effectively. The greatest need for phosphorus in maize occurs in the phases from germination to 6-8 leaves and during grain formation and maturation. It is essential that phosphorus fertilisation take into account the level of this nutrient in the soil. Mineral phosphorus fertilisers should be applied in full dose in the autumn, after harvesting the forecrop preceding the maize. A starter dose of ammonium phosphate can also be applied under the maize root. On lighter soils, the recommended fertilisation doses can also be applied before seeding in spring. Fertilisation doses vary depending on the forecast yield and what maize will be used for. For grain maize, with an assumed yield of 9 t·ha^{-1}, the phosphorus fertilisation rate should be around 95 kg·ha^{-1} P_2O_5. In the case of forage maize, the phosphorus dose should be increased to about 100-120 kg·ha^{-1} P_2O_5, assuming a green matter yield of 80-100 t·ha^{-1}. If the soil is rich in this nutrient, the applied mineral fertilisation dose should be reduced by 30-40 kg P_2O_5. Properly adjusted soil pH and rich biological life promote the availability of phosphorus in the soil. The recommended pH is between slightly acidic and neutral (6-6.8). Often, especially in farms that practice regenerative farming, phosphorus reserves in the soil are high and it may be that there is no need to replenish these reserves significantly. However, when soil is deficient in phosphorus, it should be applied at a rate of 125% of the phosphorus calculated for the expected yield.

Potassium fertilisation

The highest demand for potassium in maize takes place from the 5-6 leaf stage until flowering. Potassium uptake during this period exceeds that of nitrogen and phosphorus. The availability of potassium in the soil helps the plant to manage water efficiently, which has a positive effect on aboveground and root growth, flowering, kernel formation and increases resistance to disease and unfavourable habitat conditions. Depending on the expected grain or green matter yield, potassium doses will vary. For a yield of 5-10 kg·ha^{-1} of maize grain, they range on average from 70 to 140 kg·ha^{-1}. Maize grown for green matter has greater need for this nutrient and doses average 150-250 kg·ha^{-1}, depending on the expected yield of green matter. Potassium fertilisation should be adjusted to the nutritional needs of the crop, but also to the abundance of this nutrient in the soil. Maize fertilisation should ideally be carried out with potassium sulphate, preferably with an extra dose, due to the very rapid uptake of potassium in the first 30 days of maize growth.

Micronutrient fertilisation

In addition to macronutrients, maize needs micronutrients for growth and development. Zinc, boron, copper and manganese are the most important micronutrients in maize cultivation. In regenerative farming manure is a valuable source of micronutrients. Fields fertilised naturally should not be deficient in essential micronutrients. However, if symptoms of deficiency of any of the elements are found, foliar compound fertilisers can also be applied additionally. Foliar fertilisation can be applied from the 6 leaf stage until maize reaches approximately 40 cm in height. A total of 3 applications are recommended, every 6-10 days. Maize is particularly sensitive to zinc deficiency and also shows a high demand for this nutrient. To produce 1 tonne of grain, maize needs as much as 70-95 g of zinc. Zinc facilitates the efficient use of nitrogen fertilisers and also increases the drought resistance of the crop. High zinc deficiencies are particularly observed when maize is grown in monoculture, which is why it is so important to practise thoughtful crop rotation. Zinc deficiency also occurs in fields over-fertilised with mineral phosphorus. Zinc deficiencies can be prevented by regularly testing the level of this element in the soil and adjusting fertilisation rates accordingly. Although boron is taken up by maize in much smaller quantities, it is also an important micronutrient for this crop. Maize plants take up between 9-12 g of boron per tonne of grain produced. Since boron plays a very important role in pollination and grain formation, it is recommended to provide boron fertilisation at the 5-6 leaf stage, when ear primordium is forming. It is essential for proper development of the maize roots as well as the aboveground parts of the plant.

Sulphur and magnesium fertilisation

Sulphur is an important mineral required for proper plant growth and development. In recent years, in some areas the low sulphur reserves in soils have led to a shortage of sulphur in crops. For maize plants, it is particularly important because when sulphur is lacking, the protein content of the plant decreases and plant growth is inhibited. Fertilisation with sulphur is particularly important in high-yielding crops with high levels of nitrogen fertilisation, because it affects how efficiently nitrogen is used. Sulphur deficiencies in the soil can be corrected by applying potassium sulphate, ammonium sulphate or simple superphosphate.

The demand for magnesium increases during the period of grain formation and maturation. Maize may take up 30 to 70 (80) kg MgO per hectare annually. The type and amount of magnesium fertiliser should be chosen according to the pH and magnesium level in the soil. Lime and magnesium fertilisers are recommended for acidic soils, while magnesium sulphate fertilisers are recommended for neutral soils with a low magnesium content. It is also possible to apply magnesium together with the NPK basic fertiliser, particularly on soils with adjusted pH and average Mg content. Fertilisers that are particularly suitable for use in maize cultivation are kieserite, kainite, magnesium limestone or calcium magnesium carbonate. It is recommended to apply magnesium fertilisers in autumn. Foliar fertilisers are also an effective way of supplying magnesium to maize plants; this is particularly recommended at critical growth stages: the 5-8 leaf stage.

pH regulation and the role of calcium in regenerative maize cultivation 3.7

Soil pH regulation is a very important element of agrotechnology in regenerative agriculture. Although calcium is often present in the soil in sufficient quantities for maize, it is important to remember to supply it, especially with high NPK fertilisation. It should be emphasised that liming, apart from providing the mineral nutrient, also improves soil properties and mitigates the unfavourable conditions caused by soil acidification, such as: leaching of nutrients into deeper soil layers (especially alkaline ones), the occurrence of some components in forms that are more difficult for plants to access (e.g. phosphorus), poor biological activity of soils, the activation of toxic aluminium and manganese that adversely affect the development of the maize root system, reduced productivity of agroecosystems and reduced humus content in soil, poor physical properties of soils, including structural stability, impaired binding and introduction of atmospheric nitrogen into the soil by free-living bacteria and bacteria that coexist with legumes (the cultivation of which is recommended in regenerative agriculture), increased weed pressure (weeds tend to grow better than crops on acidified soils). Therefore, the primary purpose of liming is to reduce the acidity of cultivated soils and to obtain an optimum soil pH. Maize is one of the species that reacts very strongly to soil acidity. The optimum pH for maize is 6.0-7.5. If the soil pH is lower, it is necessary to correct the soil by liming in autumn or spring. Ideally, lime fertiliser should be applied after harvesting the forecrop, so that there is sufficient time to correct the soil pH and improve soil health before sowing maize. Production figures show that maize yield can be up to 25 per cent higher with a regulated pH compared to maize grown in unbalanced soil.

Weed, pest and disease control 3.8

Regenerative cultivation of maize aims to create the best conditions for its growth from the earliest stages of development to full maturity. A large part of the agronomic activities recommended in regenerative cultivation can be regarded at the same time as preventive measures against pathogens, pests and weeds. Regenerative agriculture focuses particularly on soil health, which also keeps crops in good health, makes them grow fast, and ensures high availability of nutrients and water in the soil. Good plant vigour increases their resistance to diseases and pests and improves their ability to compete against weeds.

From the very start of introducing maize into the rotation, many diseases and pest pressures can be prevented by selecting a suitable location for maize cultivation, which makes controlling the various pressures much easier. Crop residues are a significant source of diseases and pests in maize fields, which is why increased pressure in terms of pests and diseases is often observed in monocultures (Fig. 30). In regenerative maize cultivation, maize monocultures should not be established. Weeds, pests and diseases should be managed by a well-planned crop rotation.

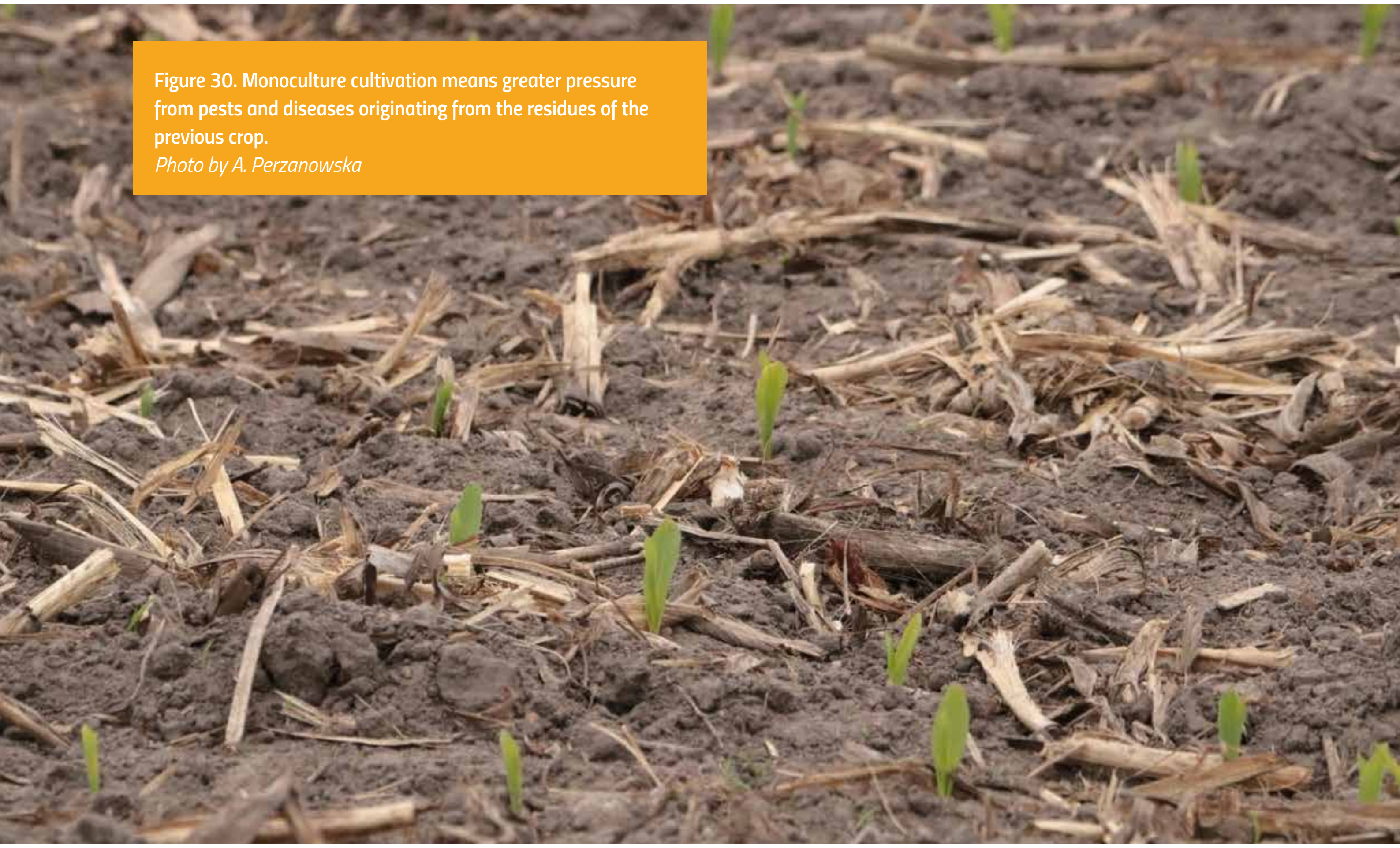

Figure 30. Monoculture cultivation means greater pressure from pests and diseases originating from the residues of the previous crop.
Photo by A. Perzanowska

Weed, pest and disease control in regenerative maize cultivation also puts great emphasis on careful planning of fertilisation, regulation of soil pH, selection of stress-resistant varieties and non-chemical methods of controlling the above problems. Chemical treatments of maize plantations are applied when necessary and in accordance with good agricultural practice.

Weed control

Growing maize in wide rows, a low plant density per m^2 (8-10 plants per m^2) and a long emergence period are conducive to weed infestation in maize. The plant provides virtually no competition for weeds in the period after seeding, which facilitates their expansion. The list of species that can appear as weeds in maize fields includes more than 100 species, but about 40 species are the most frequently observed. These are both monocotyledonous and dicotyledonous weeds and include the following: **lamb's quarters, creeping thistle, red-root amaranth, lady's thumb, cleavers, chickweed, European black nightshade, common horsetail, field bindweed, black-bindweed, common windgrass, small-flowered crane's-bill, common mugwort, cornflower, and in particular weeds from poaceae family, such as cockspur and foxtail.** Growing maize in simplified crop rotations or monoculture facilitates monoculture of noxious monocotyledonous weeds such as cockspur and foxtail. Red-root amaranth, field bindweed, common knotgrass, and other weeds that compete with maize plants from the earliest growth stages can also be a problem (Fig. 31 - 32). It shows that maize needs to be grown in rotation with other crops.

Figure 31. Growing maize in monoculture can lead to a monoculture of weeds that are difficult to control, such as cockspur.
Photo by A. Perzanowska

Figure 32. Domination of one specific weed species, common knotgrass, in a monoculture of maize.
Photo by A. Perzanowska

In regenerative maize cultivation, weed control starts as early as during the cultivation of the forecrop and other plants preceding the maize crop. It is implemented by controlling weeds in the forecrop and other plants in the rotation on a regular basis by an appropriate selection of the forecrop that leaves the field weed-free, as well as growing a crop in rotation with maize that is a different species and is gown in different time (spring and winter). Weed pressure is also reduced by intercropping with fast-growing species that win competition with weeds emerging from the soil weed seed bank, leading to its depletion. When selecting species for intercrop sowing, it is also possible to take advantage of the negative allelopathic effect of intercrop residues on weeds - for example, cereal crop residues inhibit the germination of weeds such as lamb's quarters or amaranth, which often accompany maize plants. Buckwheat has a negative allelopathic effect on weeds, especially couch grass. Combining the allelopathic effect of crop residues with minimum cultivation of the soil surface between seeding crops or leaving intercrop residues as mulch is important for controlling weeds using non-chemical methods. Reducing the weed seed bank in the surface layer of the soil is particularly important in reduced tillage methods which, unlike ploughing, do not involve turning the soil, during which new weed seeds are brought to the surface from which they can easily germinate. Therefore, the gradual reduction of the weed seed bank in the topsoil leads to a significant reduction as far as weed problems are concerned in subsequent years of reduced tillage.

Furthermore, in the case of maize, seeding in wide rows every 75 cm enables inter-row cultivation. A distance of this size between the rows of growing plants can fit a tractor tyre and allow weeders and cultivators to drive between the rows. Harrowing, which mechanically destroys emerging weeds, is often carried out after seeding and during the initial period of maize growth. This traditional mechanical method of weed control is still frequently used in maize cultivation up to the point where plants are too tall for the tractor to drive into the canopy. Harrowing and weeding the canopy destroys about 30-50% of emerged weeds and for that reason, mechanical methods are often supplemented by chemical weed control methods using herbicides.

In regenerative maize cultivation, the herbicides should only be used as a follow-up to preventive and non-chemical methods. It is important to use them following the recommendations on the packaging, at the appropriate developmental stages of maize and weeds, which is crucial to ensure that they are effective. Chemical weed control methods are used when weeds are at the beginning stages of their development, and herbicides are most effective when most weeds are still at the cotyledon stage. It is recommended to use microdoses - a mixture of low doses of preparations, in foliar treatments or systemically, applying products onto the soil and leaves. The use of divided doses and joint use of herbicides with adjuvants should be practised, which makes it possible to reduce the doses of plant protection products. It is also recommended to limit the number of treatments with the same herbicide or with a similar mechanism of action on weeds, and to use mixtures of herbicides with different mechanisms of action. Precision farming techniques can also be successfully employed in chemical weed control. It has a positive effect on the efficacy of the products and reduces the environmental risks associated with their use. Table 8 shows examples of herbicide active ingredients suitable for use in maize, subdivided by mechanism of action and groups of susceptible weeds.

Table 8. Examples of herbicide active substances authorised for use in maize

Active substance	Mechanism of action of the active substance according to HRAC	J-monocotyledonous weeds D- dicotyledonous weeds
Isoxaflutole+thiencarbazone-methyl	F2, B	J+D
Tritosulfuron+dicamba	B, O	D
S-Metachlor	K3	J
Bentazone	C3	J+D
Mesotrione	F2	J+D
Tritosulfuron+dicamba	B, O	D
Mesotrione+terbuthylazine	F2, C1	J+D
Rimsulfuron	B	J+D
2.4-D	F2	D
Florasulam	B,O	D
Dicamba	O	D
Pirydate	C3	D
Thifensulfuron-methyl	B	D
Terbuthylazine+S-Metachlor	C1, K3	J+D
Clomazone+mesotrione	F4, F2	J+D
Isoxaflutole	F2	J+D

Source: Own elaboration on the basis of Krawczyk and Kierzek (2023)

Pest management and control

Reduction and control of pests In recent years, as a result of increased temperatures, increased maize acreage and intensification of production, there is a noticeable increase in the incidence of diseases and pests in maize plantations. The most common pest in maize cultivation is the European corn borer. The caterpillars of the European corn borer feed on the cobs and stalks, leading to their damage (Fig. 33 and 34), as well as on panicle rachis, leading to their breakage and drying out, thereby shortening the pollen season and reducing the amount of pollen. Plantations are also affected by aphids, turnip moths, wireworms or grubs, as well as frit fly. The corn rootworm is also a problem in maize cultivation, as it damages the roots of the plants, inhibiting the growth of the whole plant and possibly leading to lodging. The problem with this pest is expected to increase in the coming years. The same applies to corn earworm and seedcorn maggot.

Figure 33. The European corn borer is a common pest of maize - its caterpillars eat the kernels out of the cobs, damage the cob rachis and nibble at the base of the cobs, which can lead to the cobs breaking off on their own.
Photo by A. Perzanowska

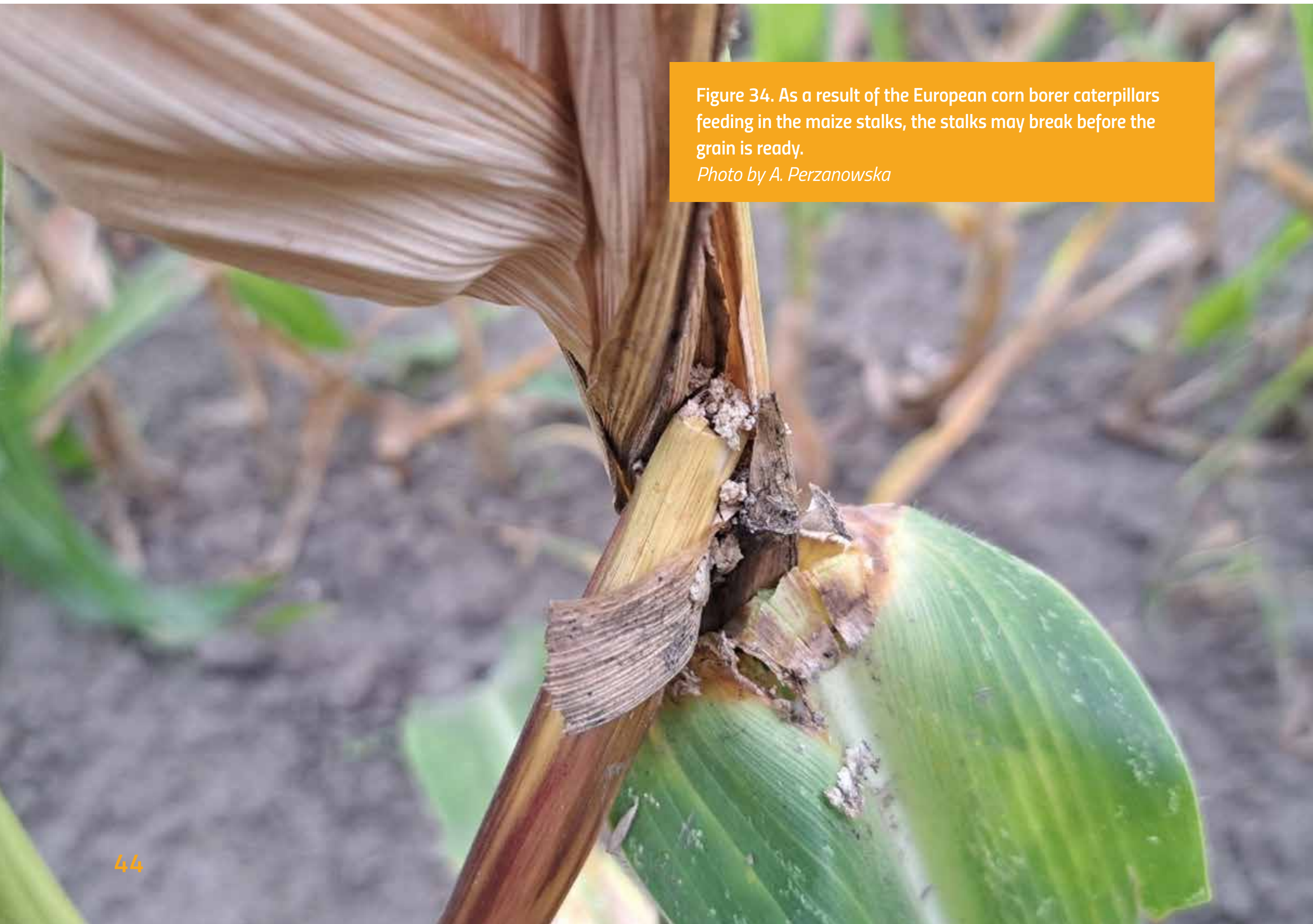

Figure 34. As a result of the European corn borer caterpillars feeding in the maize stalks, the stalks may break before the grain is ready.
Photo by A. Perzanowska

The severity of the pest problem in maize largely depends on how often maize is grown in the same field and in proximity to other maize crops and even other cereals, as well as weed pressure. When planning the crop rotation, it is therefore important to ensure that maize is not grown in neighbouring fields in subsequent years. By doing so, pests that have overwintered in maize residues are then not able to move to the marginal rows of the new crop. Other crops, such as winter wheat or winter barley, can also be a source of pest pressure in maize because adult frit flies can fly into maize plantations. The presence of weeds with thick stems in the vicinity of maize fields may be a source of invasion by the European corn borer, whose caterpillars overwinter in the stems of these weeds. Pest pressure also depends on the region, weather conditions, the activity of natural enemies or the farming system.

Inspection of the plantation and frequent monitoring of the number of pests allow a rapid reaction. In regenerative agriculture controlling pests and weeds relies primarily on non-chemical methods and damage threshold. As regards the control of the most dangerous and widespread pest of maize, the European corn borer, farmers use biological preparations based on the borer's egg parasite, the trichogramma (especially in sweetcorn plantations), or preparations based on Bacillus bacteria, which are applied in maize fields using special sprayers designed to work in maize fields at later stages of development. The presence of beneficial insects, which are the natural enemies of maize pests, in the plantations should also be encouraged by maintaining landscape features in the agricultural landscape that provide habitats for them to live and breed. If ladybird or green lacewings larvae are abundant in the plantation, chemical control of aphids can be abandoned.

Only when these methods fail and the risk of exceeding the economic damage threshold is high will it become necessary to use insecticides. This situation occurs when there is high pest pressure in the maize canopy, often caused by poor management of cultivation technology and agricultural land. Table 9 provides examples of active substances used to control pests in maize crops. Using insecticides for plant protection should be done according to the label guidelines and the principles of good agricultural practice.

Table 9. List of active substances in insecticides recommended for pest control in maize

<table>
<tr><th>Active substance</th><th>Targeted pest</th></tr>
<tr><td>Cyantraniliprole</td><td>Turnip moths, wireworms</td></tr>
<tr><td>Cypermethrin</td><td>Corn rootworm, wireworms</td></tr>
<tr><td>Tefluthrin</td><td>Wireworms, corn rootworm</td></tr>
<tr><td>Bacillus thuringiensis subsp. kurstaki strain EG 234 (bioinsecticide)</td><td>European corn borer</td></tr>
<tr><td>Acetamiprid</td><td rowspan="4">European corn borer</td></tr>
<tr><td>Spinosad</td></tr>
<tr><td>Tebufenozide</td></tr>
<tr><td>Chlorantraniliprole</td></tr>
</table>

Source: Own elaboration on the basis of Mrówczyński and Strażyński, 2024

Maize plantations may also be damaged by animals, especially birds and game - wild boar, deer, and to a lesser extent roe deer. For that reason, maize crops should not be located in forest clearings or in close proximity to forest complexes. Chemical repellents and noise repellents are effective in deterring wildlife.

Disease management and control

The risk of diseases is high in all maize-growing regions. These diseases are not only responsible for the decline in grain yield, but also impair the quality of the harvested crop. In recent years the greatest threat have been diseased caused by fusarium fungi: cob fusariosis, root rot and stem fusariosis, as well as corn smut and head smut (Fig. 35). In accordance with regenerative disease prevention principles, maize varieties with greater resistance to diseases, especially fusariosis, should be selected for cultivation.

The primary source of infection in the case of most fungal diseases is the infected soil, crop residues or seed material. For this reason, diseases occur more easily if there are agronomic simplifications of various kinds, such as monocultures (Fig. 36), reduced tillage systems, lack of careful straw shredding, incorrect crop rotations and seeding of grain of unknown origin. Agrotechnical strategies should aim to address these pressures to reduce the incidence and severity of diseases. Agronomic methods of disease control include balanced fertilisation and seeding in optimal conditions for maize, which improves plant health and its potential to overcome potential infections. Soil cultivation and residue management may also be a tool in reducing the pressure of disease-causing fungi in maize fields where increased disease pressure is observed and diseases are spread through plant residues to the succeeding crop. Reduced tillage should not be abandoned, but managed appropriately. Mechanical shredding of crop residues through shallow reduced cultivation can effectively break up mycelium hyphae network, thus hindering the transfer of microbial activity to the next crop in the rotation and consequently reducing the risk of disease. On the other hand, leaving crop residues on the soil surface will slow down the warming of the soil and increase soil moisture, which can promote the proliferation of fungi - therefore, especially in colder regions, it is beneficial to introduce simplified cultivation technologies that move crop residues out of the seedbed zone, such as strip-till.

Figure 35. Increased infestation of plants with smut head can be a problem, especially in monocultures and when maize is grown on the same field over and over again.
Photo by A. Perzanowska

Figure 36. A frequently observed problem in maize monocultures is the increased incidence of maize head smut. *Photo by A. Perzanowska*

Protective agrotechnical methods in regenerative maize cultivation can be supplemented, if necessary, by chemical methods. Table 10 shows some of the active substances used to protect corn against diseases.

Table 10. Examples of fungicide active substances effective in the case of maize

Active substance	Targeted disease
Trichoderma asperellum (biological fungicide)	fusarium root rot and stem fusariosis , cob fusariosis
Azoxystrobin	Northern corn leaf blight, corn eyespot disease
Mefentrifluconazole	Northern corn leaf blight, corn fusariosis
Azoxystrobin+tebuconazole	corn eyespot disease
Fluopyram+prothioconazole	Northern corn leaf blight, corn eyespot disease
Metalaxyl+prothioconazole	seedling blight
Fludioxonil	seedling blight (moderate control), botrytis (moderate control), downy mildew

Source: Own elaboration on the basis of Korbas et al., 2024

3.9 Harvest and storage

The time and technology of harvesting and storing maize depends on what it is used for.

Grain maize

Crops grown for grain are harvested at maturity from late-waxy stage to full maturity of the grain. With some modification of the harvesting method, the grain can be harvested together with the cores and husks. The harvest is ensiled, producing silage from maize grain and cob cores, called CCM (from corn cob mix). The harvesting method, properties and intended use of the obtained products are shown in Table 11.

Table 11. Use of maize grown for grain

Harvested material	Grain	Grain + 50-90% cores	Cobs with no husks	Cobs with husks	Whole plants
harvesting method	special combine with a threshing system or a customised combine harvester for cereals	cob picker	forage harvester adjusted to harvest cobs		forage harvester
Maturity grain	full		late-waxy to full		
Type of preservation	drying, ensilage	ensilage crushing	ensilage crushing	ensilage	drying
Product use	wet grain or dried	CCM (CCM-I)	corn cob meal (CCM-II)	cob chaff (CCM-III)	dried corn
Fodder and its characteristics	commercial grain, feeding poultry and fattening pigs, processing at distilleries	fodder: fattening pigs	fodder: fattening pigs and breeding pigs	fodder: sows, beef cattle, milk cattle	fodder: beef cattle, milk cattle, component of concentrated feed

Source: Own elaboration on the basis of Michalski (2004)

Bruised grain or different variants of CCM are used as a concentrated feed for ruminants, as well as a cheap concentrated feed for pigs. It is much less common to harvest maize to dry the whole plants, due to the high cost of crop dessication.

The grain maize harvest is usually in September-October, depending on the earliness of the variety. Fully mature grain can be recognised by the presence of a slight blackening at the base of the kernel - the so-called black layer. Threshing of the cobs with a combine harvester suitable for maize harvesting is carried out at a grain moisture content as low as 38%. Early and mid-mature varieties mature as early as September, while mid-late varieties mature from 1 to 2 weeks later. A later harvest also means that the moisture content of the grain is 2-5% higher, while the moisture content of the grain when the earlier varieties are threshed is 25-30%. The lower cost of desiccating the grain in this case compensates for the usually slightly lower yields of earlier varieties compared to later varieties. With a sunny and dry autumn, each day the grain loses moisture after reaching threshing maturity is beneficial. However, delaying harvest for too long can increase losses in yield and grain quality as a result of bird, pest or disease pressure.

To harvest maize grain by combine harvester, the entire sequence of subsequent operations must be well coordinated - from the collection of wet grain from the field to its prompt transport to the drying area and preservation. Desiccation of the grain should take place immediately after harvesting to avoid overheating, which has a negative impact on the quality of the grain. Overheated grain that is not dried quickly is not suitable for animal or human consumption. Harvested wet grain can also be ensiled in gas-tight silos or plastic sleeves. Before ensiling, the grain should be chopped or crushed.

To produce CCM from grain maize, the grain is usually harvested at the beginning of full maturity - at this stage, the grain moisture content is 38-40% and the dry matter content of the cobs is 53-55%. Lower grain moisture content at the time of harvesting for CCM can make it more difficult to crush cobs and hinder the process of ensiling. Depending on the type of CCM, the grain is harvested with cob cores and even with husks. If, for some reason, it is not possible to harvest the maize later, the cobs for CCM with cores and grain can be harvested at waxy maturity and earlier, but the feed from such cobs has a lower nutritional value. Harvesting cobs with outer leaves should preferably be done at late-wax maturity of the grain. Before ensiling, cobs and grain should be well shredded - particles with a diameter of 2 mm should make up at least 80% of the mass prepared for ensiling. Good shredding and, in particular, the precise damage to aleurone of the grain improves the use of feed by CCM-fed animals.

Silage maize

Harvesting whole plants should be carried out at the appropriate maturity of the plant - the greater the maturity, the greater the proportion of cobs and grain in the yield, and the smaller the proportion of fibre from the rest of the biomass. For this reason, harvesting maize for silage should not be rushed, as its feed value increases with maturity. The optimum condition for obtaining a good energy/fibre ratio is to harvest maize at a dry matter content of 30-36% in the whole plant. If the dry matter content is higher, there can be problems with good biomass breakdown, including the proportion of damaged kernels and the quality of the silos and the tightness of the cover. To evaluate the maturity stage of maize grain and the dry matter content of the plants, one thing to look for is the so-called milk line, which separates the vitreous starch from the soft floury starch. It can be seen when the cob is broken in half (Fig. 37). If the milk line (measured from the tip of the kernel) is at 1/3 of the height of the kernel, the dry matter content is between 25-26%, if at half the height of the kernel, the dry matter content approaches 30%, and at 2/3 of the height of the kernel it is 31-32%. Once past 2/3 of the height and a visible milk line at the tip of the kernel, the dry matter content is 33-34%, indicating the optimum time to harvest. When the weather is dry and the maize is in poor condition, the dry matter content of 33-34% is reached when the milk line is at 2/3 of the kernel height. The evaluation of dry matter content based on the position of the milk line is only an approximation. A more precise estimation of the dry matter content will be obtained using the gravimetric method.

Depending on the silage production technology, maize can be seeded at different densities and harvested at different grain maturities. For standard silage, which is suitable for feeding dry cows and young stock, maize is sown more densely (12-14 seeds per square metre) and harvested at waxy maturity where the dry matter content is usually between 28-32%. Maize plantations harvested later (grain at near-full maturity) and sown less densely (8 - 9 seeds·m-2) yield a biomass with a dry matter content of 33-36%. Silage from such maize is a high-energy silage, recommended for feeding high-yielding dairy cows. To increase the energy concentration in such silage, the maize can be cut higher or crushed grain added can be added to the ensiled biomass. When harvesting maize from late waxy maturity to the beginning of full maturity (the proportion of dry matter exceeds 32%), the material for ensiling should be well shredded - thicker pieces of stalks should be torn and each kernel damaged (Fig. 38). Silage from such biomass has a better digestibility and better forage use efficiency.

Figure 37. The position of the milk line is an approximate indicator of the dry matter content of the crop and the optimum time to harvest maize for silage.
Photo by A. Perzanowska

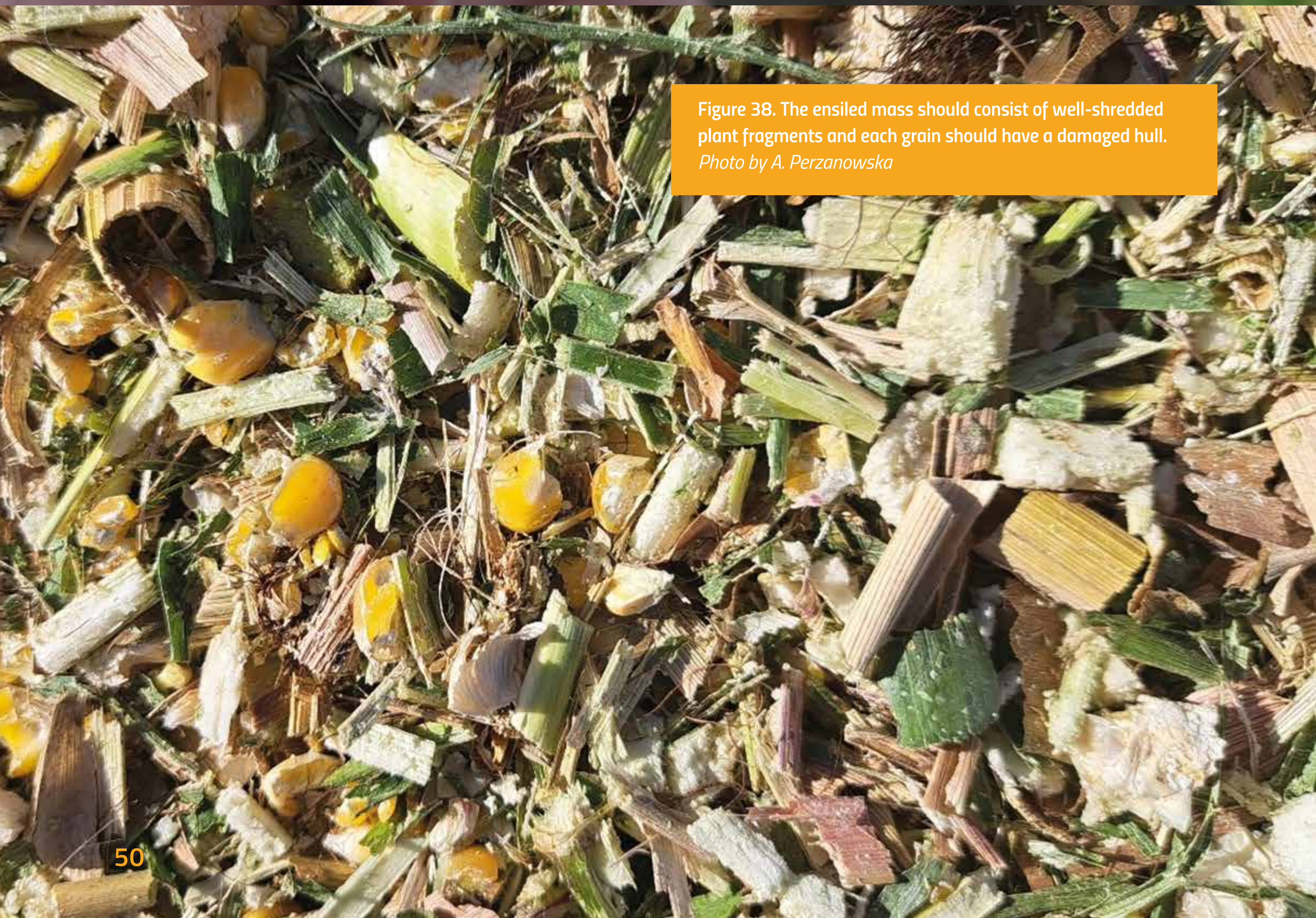

Figure 38. The ensiled mass should consist of well-shredded plant fragments and each grain should have a damaged hull.
Photo by A. Perzanowska

Shredded maize biomass will ensile well and there are many options for how it can be done. Maize can be ensiled in plastic sleeves, tower silos, pits, bunkers and drive-through and front-load silos. It is very important to ensure that the ensiled forage is well compacted to remove oxygen from the ensiled mass and ensure proper lactic fermentation, limiting the growth of mold, yeast and acetic fermentation bacteria, which impair the palatability and intake of the silage by the animals fed with it. It is best to use the heaviest tractors available, without dual wheels, to compact the ensiled mass. After good compression, the stockpile should be quickly and tightly covered, preferably using thick films with high mechanical strength. The sheets should also be protected from being blown away by the wind, e.g. by covering the stockpile with dirt (Fig. 39).

Figure 39. The silage stockpile should be well formed and protected so that the lactic fermentation process can take place.
Photo by A. Perzanowska

Maize is type of crop that is harvested relatively late regardless of what it is cultivated for. Unfortunately, often the later the harvest date, the worse the weather conditions and the greater the moisture content of the soils. Especially if the autumn is cool, the drying of the soil after rainfall is slower. Multiple runs over the field by combine harvester, tractor and trailers with grain or maize biomass for ensiling in such conditions can result in the formation of tracks and also compaction of the deeper layers of the soil. It is therefore important that, if possible, maize harvesting is not carried out during periods of high soil moisture, shortly after the rain.

4

A LIST OF PRACTICES AND ANALYSIS OF BENEFITS

To conclude, regenerative maize farming takes into account the following:

- **maize is one of the most important crops worldwide**, as well as in Europe, and is planted in a variety of soil and climatic conditions,

- **regenerative maize production rules out maize monocultures and crop rotations,** which can contribute to the deterioration of soil quality and plant health, especially increased pressure from pests, weeds, and diseases,

- **in the cultivation of maize, it is very important to select varieties** that are well adapted to the soil and climatic conditions and to the intended use of the grain or biomass,

- **the impact of maize on the soil and its health depends on what that plants are used for** and is slightly different for grain and silage varieties. Silage varieties have a greater negative impact on the soil organic matter which is why silage maize should be used in rotation with intercrops that will compensate for this degradation,

- **maize straw left after harvesting grain maize and incorporated into the soil to some extent compensates for the deterioration of the physical properties of the soil;** if the straw from maize or other rotation crops is managed on the field, it should be well shredded and evenly distributed over the field surface,

- **prior to the cultivation of maize, there is time to cultivate the intercrop mixes inherent to regenerative agriculture:** stubble catch crops, winter intercrops and interseeding. The choice of the type of catch crop should depend on the purpose of its cultivation and the soil and climatic conditions of the field,

- **the cultivation of maize in wide rows exacerbates the effects of water and wind erosion on the soil.** Hence, it is recommended to apply agrotechnical methods that improve the resilience of the soil to these adverse effects, such as reduced tillage, which means that plant residues remain on the soil surface during the maize-growing period, and other methods that improve the stability of the soil structure,

- **practising reduced tillage and introducing cover crops and soil-building crops into the rotation with maize,** cultivated as the main crop and as intercrops, reduces the occurrence of hardpan layer and limits soil compaction, which hinders proper plant development and increases susceptibility to stresses and diseases,

- **maize is a crop with high fertiliser requirements,** so its fertilisation should be balanced and carried out on the basis of the nutrient availability of the soil and the nutritional needs of the plants at different levels of yield,

- **natural and organic fertilisation, as well as foliar feeding can be used in maize cultivation.** Farmers should follow the principles of good agricultural and environmental practices. Mineral fertilisation should be supplementary to natural and organic fertilisation and should make up for soil nutrient deficiencies in the soil,

- **maize is a plant that is very sensitive to soil acidification** and should be cultivated in conditions with a pH close to neutral; it is essential to carry out liming when the pH is lower to regulate the soil pH, but this also influences biological activity, soil structure, availability and uptake of nutrients by the maize and, consequently, the effectiveness of fertilisation,

- **for plant protection, all non-chemical methods should be used first,** including selection of varieties resistant to fusarium diseases, properly planned crop rotation, seeding and cultivation methods at optimal times, use of balanced fertilisation to improve plant resistance, use of biological and mechanical protection methods as alternatives to pesticides, protection of natural beneficial organisms, and isolation of crops from plants that may be sources of pathogens,

- **all cultivation should be carried out at optimal soil moisture levels** in order to minimise damage to the structure and profile of the soil and to prevent excessive compaction of the topsoil and subsoil; any soil diseases identified should be dealt with,

- the quality of a maize crop is determined not only by the agronomic practices, but also by the timing of grain and biomass harvesting and the way in which they are preserved, which is why it should be well planned regardless of whether maize is grown for grain or silage.

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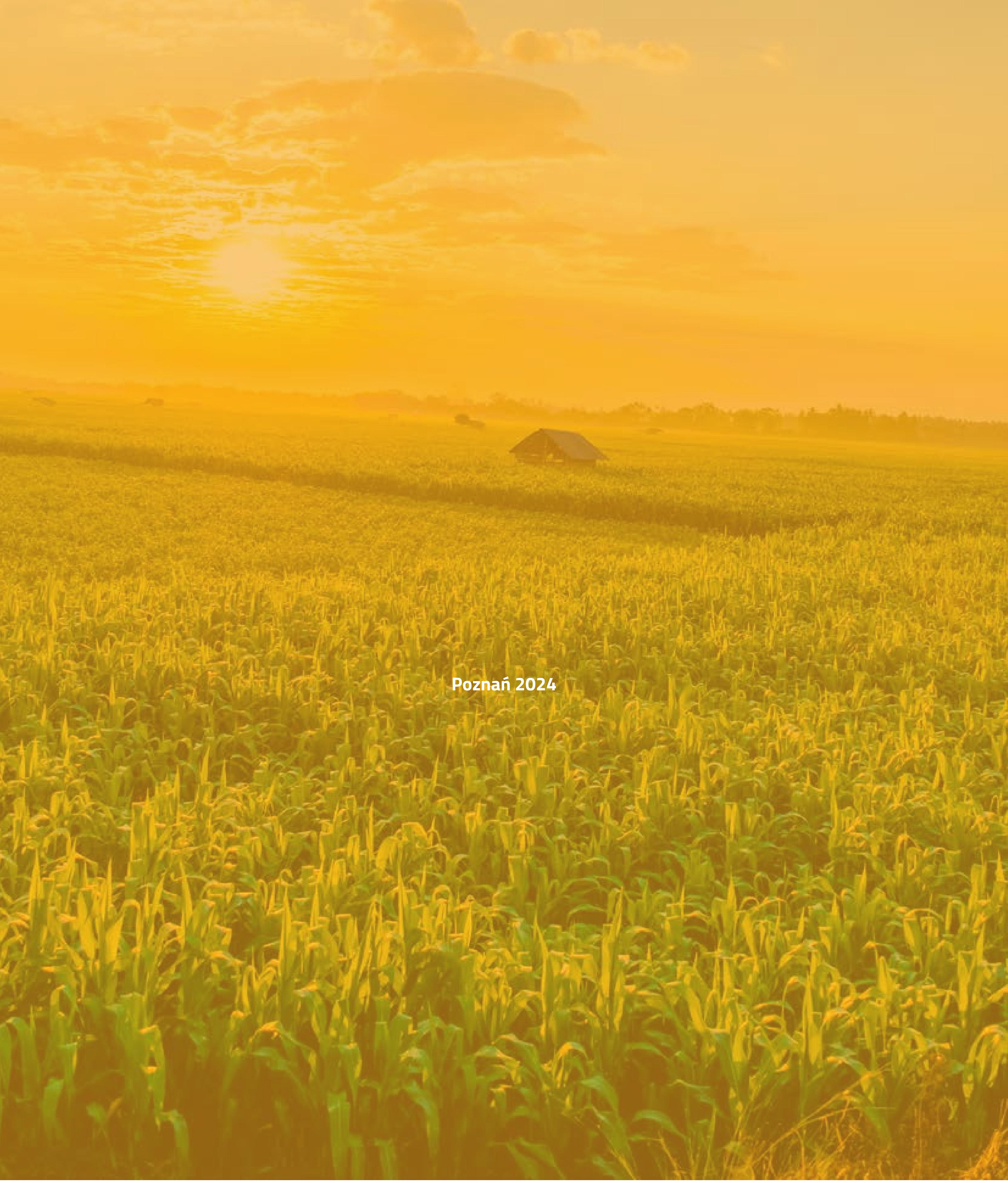

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