

# Genes against Drought

In many regions of the Earth, agriculture is threatened by a lack of water. Therefore, new plant varieties must be developed that are especially resistant to drought. For scientists at the **Max Planck Institute for Plant Breeding Research** in Cologne, barley is an ideal model for understanding the genetic strategies plants use to adapt to drought.

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**P**lants have developed various strategies to survive and grow in the presence of drought. For example, they avoid damage from a lack of water by growing more roots to increase their water uptake, or by reducing leaf transpiration. Plants also store and remobilize reserve carbohydrates and adjust their life cycles to survive in dry environments.

Furthermore, plants can become less sensitive to drought. Tolerance to drought stress is controlled by many genes, all of which improve the yield for a given quantity of water. For example, plants can protect their cells from a lack of water with special

proteins. These enzymes ensure that cell proteins and membranes retain their normal structure and continue to function. In addition, cells accumulate active substances, such as proline, sorbitol and glycine betaine, in their storage organelle, the vacuole. These storage compounds reduce the cells' water loss.

If all of these strategies fail, the osmotic pressure in the cell falls and the concentration of intracellular compounds rises. The resulting osmotic stress damages the cell membrane and large molecules in the plant cells. Furthermore, if the lack of water prevents photosynthesis, and the chloroplasts continue to be exposed to strong sun-

light, oxygen radicals, such as superoxides and peroxides, start to form. These directly attack enzymes and membranes in the cell and destroy them.

## **ALTERNATIVES TO GENETICALLY MODIFIED PLANTS**

At the Max Planck Institute for Breeding Research in Cologne, we are studying how barley has adapted to dry conditions. We make use of the natural genetic diversity of cultivars and their close relatives (wild forms) as an alternative to studying transgenic crops. As barley and other cereals are genetically very similar, new findings in barley can be translated to other crops, such as wheat.



Along with einkorn wheat, emmer wheat, flax and lentils, barley is one of the oldest cultivated plants. It was first cultivated about 10,000 years ago, when humans began to grow and select plants for food production. The elite barley varieties cultivated today are derived from the two-row wild form *Hordeum vulgare* L. ssp. *spontaneum*. The genus *Hordeum* comprises a total of 30 different wild varieties. After corn, rice and wheat, barley is the fourth most important cereal in the world and has the widest geographical distribution. It grows in the dry regions of the Middle East, in Tibet at altitudes of over 4,000 meters, in the sub-tropics and at the polar limit of grain cultivation.

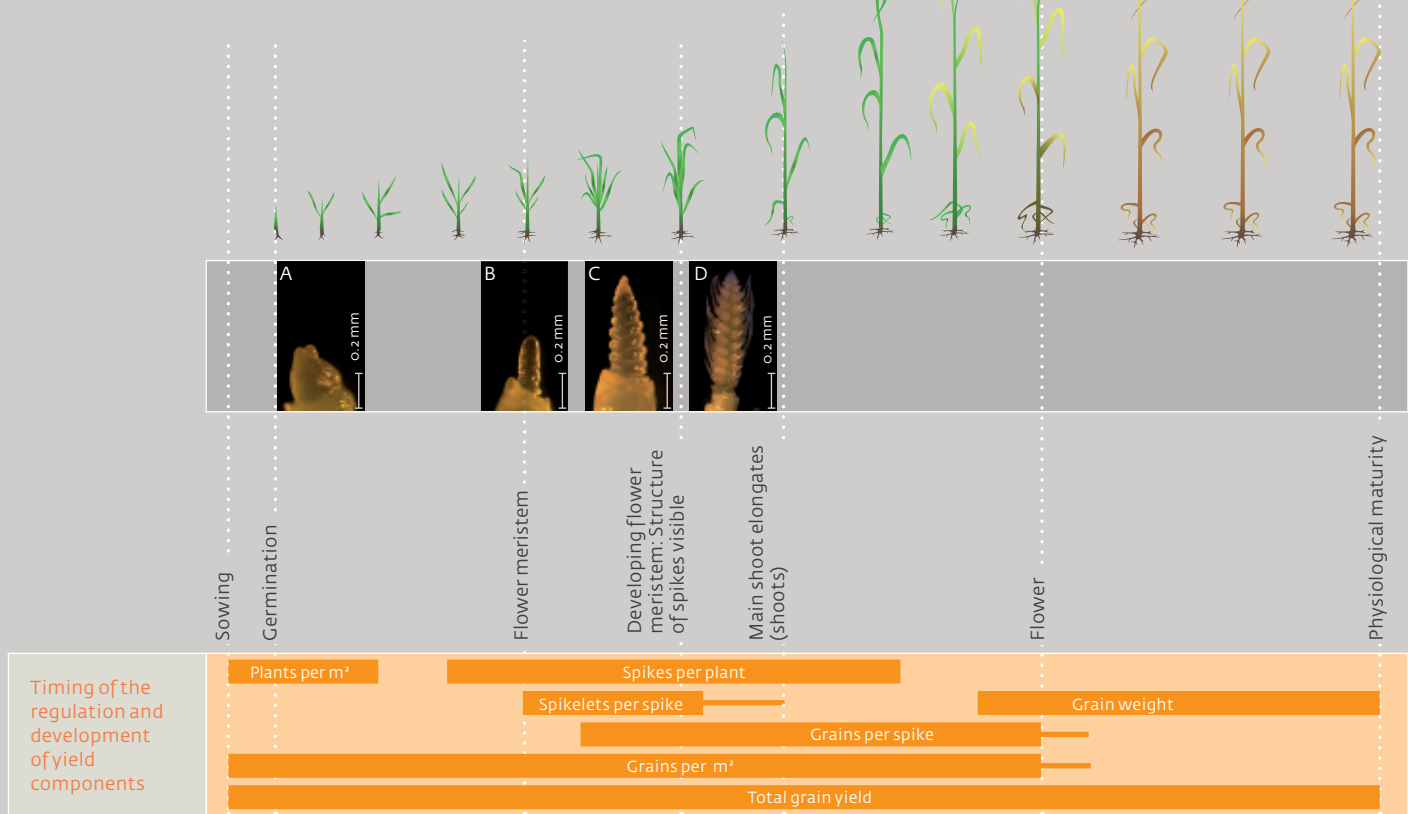
Today, most variants still grow where barley first originated and was later cultivated by humans – in the Middle East region known as the Fertile Crescent, and in North and East Africa. Barley thus holds great genetic potential for adaptation, which can be exploited to breed resistant varieties.

Barley varieties that grow in very dry locations have developed special protective mechanisms. Wild barleys from the Fertile Crescent store more anthocyanins in their stems, leaves and spikes. These pigments give the plant a red color and protect it from excessive sunlight, like a sunscreen. A dense cover of hairs on the stems and leaves also reflects the sunlight. In addition, leaf hairs

trap the moist air above the leaf surface and thus reduce transpiration and water loss from the plant. Barley can also adapt its life cycle to the surrounding temperature and to the available water. In dry, southern regions, for example, barley flowers early in the spring, ensuring that it completes its life cycle before the onset of the summer heat. In temperate latitudes, in contrast, barley develops more slowly, exploiting the longer growth period. In Germany, barley grows annually as spring barley or, like winter barley in the Mediterranean area, over the winter.

Today, four major genes are known in barley that induce flowering when the day length and temperature are ap-

There are several phases in the development of barley flowers. First, vegetative growth tissue (meristem, A) forms the flower meristem, B. From this is formed the spike with the meristem primordia (C), which then develops into fertile florets (D) as the stem elongates. The duration of each of these phases varies independently of the others and depends on both the environment and the genetic makeup of the plant. Each developmental phase affects yield in a different way: the number of spikes per plant is determined at the early developmental stage before the spike is completely developed. The number of grains per spike is determined primarily during stem elongation.



appropriate. The photoperiod response gene *Ppd-H1* in winter barley triggers flowering as soon as day length increases in spring. At the same time, the vernalization gene *Vrn-H2* counteracts *Ppd-H1*; it permits flowering only when the plant has been exposed to low temperatures. After a sufficient cold stimulus, the vernalization gene *Vrn-H1* induces the development of the reproductive meristem. In contrast, the vernalization gene *Vrn-H3*, like *Ppd-H1*, is thought to accelerate the late reproductive stages in barley.

### MUTATIONS DELAY DEVELOPMENT IN BARLEY

In contrast to winter barley, the *Ppd-H1* gene is mutated in spring barley and is therefore inactive. Moreover, the *Vrn-H2* gene is deleted. Flower development is thus delayed in spring barley under long photoperiods, and does not require vernalization, allowing the plant to make use of the long growth period in temperate climates.

We are looking for genes that influence individual phases of flower development. This would allow flowering to be fine-tuned in different environments in order to increase yield. Drought shortens the time to flowering in barley. Long photoperiods affect primarily the later reproductive stages, stem elongation and spike development. The extensive collection of wild barleys from the Fertile Crescent held at our institute is a valuable source of new genetic variants, as systematic breeding of high-yielding varieties since the beginning of the last century has increasingly narrowed genetic variation in our elite varieties. In terms of evolutionary history, though, this is a short period of time, and most of the natural ancestors of our recent cultivars can still be crossed with them.

We investigated around 900 varieties of wild barley and crossed those that vary in their reproductive development with German barley cultivars. This gives rise to barley lines with dif-

ferences in reproductive development and thus yield structure. The underlying traits and gene forms that cause this variation are passed on to the offspring. With the aid of molecular markers, we identify those regions in the barley genome that control spike development. As the barley genome has not yet been decoded, we align the identified genomic regions with the rice reference genome, which has already been sequenced. This allows us to identify flowering time genes in barley, as rice and barley are characterized by a similar gene content and gene order on the chromosomes.

### FROM THE LABORATORY TO FIELD RESEARCH

We also use findings from plant genome research on *Arabidopsis thaliana* because the pathways that trigger flower development have already been thoroughly investigated in this plant. As many of the genes and functions involved are also functional in barley,





Scientists test the positive characteristics of wild barley, such as stress resistance, in crosses between wild and cultivated barley in the field. Plants with slow stem and spike growth form particularly fertile flowers and grains and thus provide a better yield.

it is possible to draw conclusions about the genetic regulation of flower development in barley.

Studies on the regulation of flowering time in barley are first carried out under controlled conditions in the greenhouse, where we test the effect of individual environmental parameters – day length, temperature and water – on the individual genes and traits. However, we have to study the effects of the different gene forms in wild and cultivated barley in the field before they can be applied in plant breeding. For this, we work with the Center for Agricultural Research in the Dry Areas (ICARDA) in Syria; ICARDA has the global mandate to research barley and agricultural production in semi-arid regions.

At this international agricultural research center, we are examining, under natural conditions in the field, the

strategies barley uses to adapt to drought. We then carry out detailed genetic studies at our institute to identify the genes and gene regions that increase the crop yield of barley under dry conditions. This information is not only important for farmers in the Middle East, it also serves the breeding of cultivated plants in other parts of the world where they must adapt to increasingly dry summers.

We are already experiencing an accumulation of extreme weather conditions in connection with climate change. Global climate models are forecasting that, by the end of the 21st century, the Earth will be 2 to 5 degrees Celsius warmer, and that heat waves, drought periods, floods and heavy precipitation will increase. The developing countries in sub-Saharan Africa and in Asia will be particularly affected. Cal-

culations by the Intergovernmental Panel on Climate Change suggest that harvest yields in these areas could be halved by 2020.

Central and Northern Europe are among the areas that might potentially benefit from climate change, as heavier winter precipitation and higher average temperatures could increase agricultural production. For this to happen, however, today's crop plants must be adapted to the new climate conditions. This task is becoming increasingly difficult, as it is not the seasonal mean value that decides the quantity and quality of harvests, but primarily the climatic extremes. For example, continental and southern regions of Europe are already suffering from longer dry periods in the summer months. But also in Germany, grain harvests, with the exception of winter





- 1 | Pigments in the stem block part of the solar radiation and protect the plant from damage caused by too much light.
- 2 | Barley protects itself from drought: A thick layer of hairs acts like a sunscreen and reduces the transpiration of the plant.
- 3 | Barley self-fertilizes and flowers when the spikes are still in the leaf sheath. Only after successful fertilization do the spikes grow out of the leaf sheath and the flowers open and reveal the anthers.

barley, have been stagnating for the past ten years. Therefore, also scientists in Europe are researching the development of plant varieties that maximize yield per unit of water used.

In many areas of the Earth, water is in short supply. Water availability is thus the most important factor in agricultural production throughout the world. Increasing food production in the future depends primarily on whether agricultural areas can be supplied with sufficient water. In 2008, precipita-

tion was less than 150 mm in many of the farming areas in the Fertile Crescent.

Under these conditions, drought-resistant barley varieties still produce approximately 500 kilograms per hectare. To a German farmer with a yield of 60 to 100 tons per hectare, this would mean an almost total crop failure, but to a self-sufficient farmer in many regions of the Middle East, it means subsistence. They are then not forced to sell their livestock and look for work in the city. The most important objective of the breeding re-

search in Cologne and Syria is thus to decode the genetic basis for stable yields under extreme growing conditions.

Against this backdrop, in the future, stable or even rising agricultural yields will depend on the successful development of new cultivars. The cereals that will become increasingly important are those that are already an integral part of extensive farming systems and that, due to their low water use, grow in dry conditions – and these are mainly winter and spring barley. ◀

## GLOSSARY

### Spring/winter barley

Winter barley requires a cold period to develop inflorescences. It is sown in late September in Central Europe and harvested in July. Winter barley has a 20 percent higher yield, as it optimizes the use of moisture in winter. Its share of barley production has thus been on the rise for years. Spring barley, in contrast, is sown in March or April and harvested in August. Winter barley is used mainly for animal fodder; spring barley is used for malt.

### Vernalization gene

(Latin *vernus* – spring)  
A gene that inhibits flower development prior to sufficient exposure of the plant to temperatures below 10 degrees Celsius. In some plant varieties, there can be months between the cold period and flower development. Most cereals need a cold period before they flower.

### Fertile Crescent

One of the regions in which humans originally settled and transitioned from the nomadic lifestyle to farming and livestock breeding. It covers parts of Lebanon, Syria, Iraq, Iran and southeastern Turkey. Some of the globally most significant cultivated plants, such as wheat, barley, lentils and peas, and four of the five most important domestic animals were domesticated here. The closely related wild forms of crop species are still widespread in the Fertile Crescent.