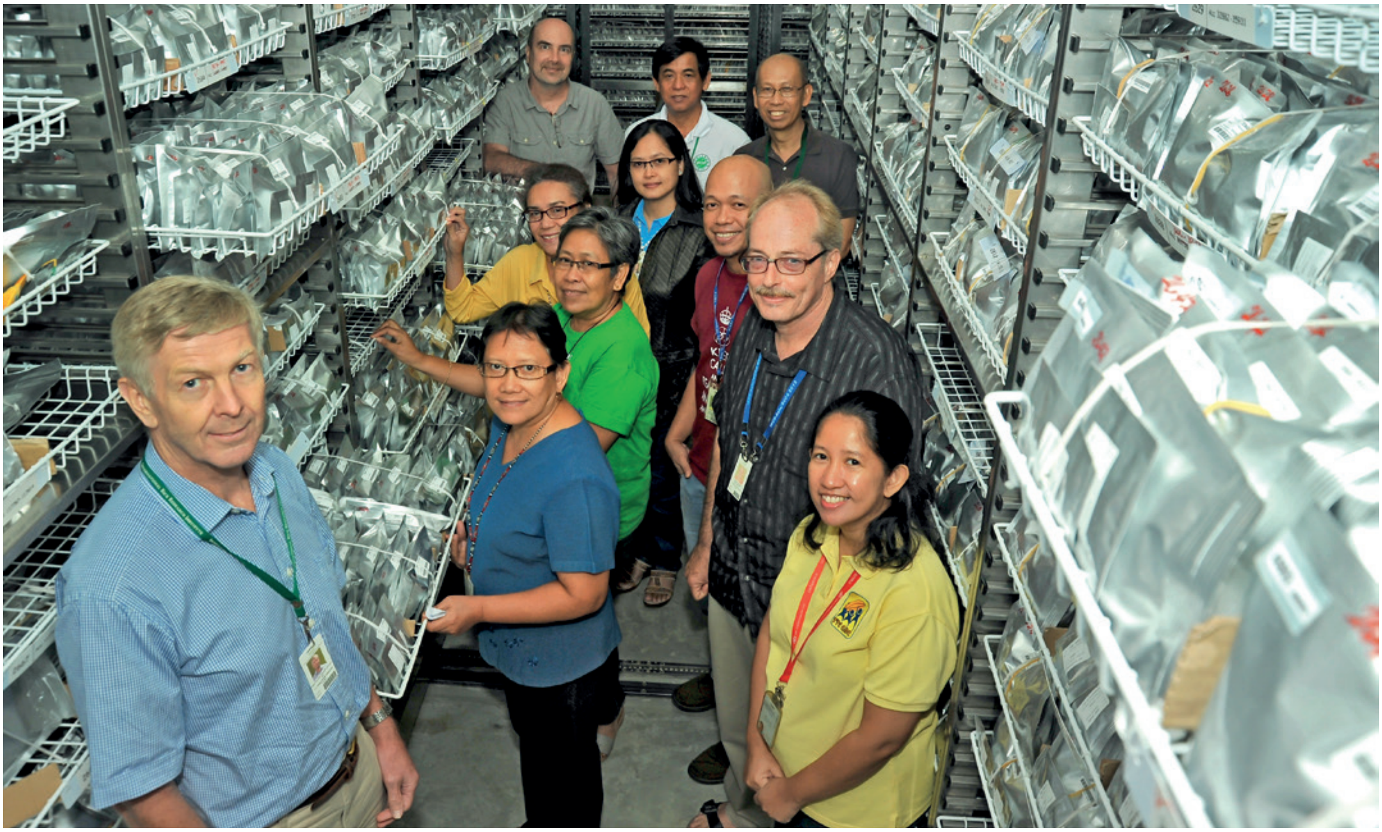

The team at the International Rice Research Institute who submitted data to the 3,000 Rice Genomes Project.

YIELD

The search for the rice of the future

Scientists are hoping to make the world's most successful crop even better.

BY FELIX CHEUNG

Two farmers in different parts of the world can plant the same species of rice, but their crops may look strikingly different. Rice has enormous genetic diversity, and scientists are now developing the ability to take advantage of it. In May 2014, a group of researchers from the Chinese Academy of Agricultural Sciences (CAAS); the research organization BGI, based in Shenzhen, China; and the International Rice Research Institute (IRRI) in the Philippines published the genome sequences of 3,000 strains of rice collected from 89 countries[1].

This endeavour, called the 3,000 Rice Genomes Project, allows scientists to identify the specific genes that control the traits that are most important for rice production. Their discoveries will undoubtedly lead to important insights into the history of rice domestication (see page S58) and, more importantly, will provide clear targets to further improve one of the world's most important crops.

Improvements are desperately needed. Advances in breeding and agriculture have greatly increased yields over the past few decades, but scientists warn that if current population trends continue, there won't be enough rice to meet demand by 2050 (see page S50). In addition, greater urbanization, water shortages, soil erosion and extreme weather resulting from climate change may threaten rice production and offset many hard-won victories. Rice researchers know they will have to push the genetics even further if they are to keep pace and ensure rice's place as a staple food in the future. They also know that alongside the molecular genetics and biotechnological advances, there is still a place for the careful interbreeding of both domesticated and wild rice strains.

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OLD-SCHOOL ADVANCES

Farmers have been using hybridization in one form or another for thousands of years, but the approach is still at the forefront of advances in rice production. In September 2013, researchers around the world applauded Yuan Longping — known as the father of modern hybrid rice — and his team at the China National Hybrid Rice Research and Development Center in Changsha when they unveiled their latest 'super rice' hybrid. The new strain, called Y Liangyou 900, yielded 14.8 tonnes per hectare — a record and more than double the average yield for rice in China[2]. In field tests the rice produced 6.6% more grains than the previous record-holder, also developed by Yuan's team. The new strain puts China, the world's largest

IRRI

rice producer, firmly on track towards its target of achieving 15 tonnes per hectare in demonstration sites by 2015 and nationwide by 2020.

Y Liangyou 900 is the culmination of 40 years of careful crossbreeding and has every trait that would be expected from a super-productive strain of rice. It has strong roots, large panicles (secondary branches), a high seeding rate and large grains, and is resistant to stresses such as drought and insect infestations. And, as Yuan notes with pride, all this has been accomplished using old-fashioned interbreeding.

Over the decades, Yuan has shown many times that a deft touch with breeding can yield great rewards. In 1973 he developed his first hybrid rice, an *indica* (long grain) hybrid of three different strains that produced 20–30% more grains than conventional varieties. Every year since then has seen an increase in the average grain yield in China. Today, modern hybrids grow in 57% of rice paddies in the country and account for 65% of the national rice output[3].

Many hybrid rice varieties are hardier and grow better than either of their parent strains, but it has not been entirely clear why. This phenomenon, known as 'hybrid vigour' or heterosis, is often seen in agriculture but seems to be especially strong in rice. An analysis[4] published in 2009 found that genes related to energy metabolism and transport are especially active in hybrid rice *LYP9*, suggesting that these genes may be particularly important in the development of hybrid vigour.

GENETIC REVOLUTION

Despite all this progress, scientists acknowledge that hybridization alone won't provide enough rice to meet future demand. They will need to identify the genes that control particular beneficial traits and use the tools of biotechnology to improve the plant. The publication of 3,000 rice genome sequences is sure to help, but even before all this information became available, scientists had already found some genes that have proven to be game changers.

As recently as the early 1960s, most rice crops were tall varieties that were prone to tipping over under the weight of large, heavy grains. The solution was the development of a shorter, sturdier variety of rice called IR8 that could deliver the same amount of grain but was less prone to tipping. Widespread use of this new variety helped to drive Asia's 'green revolution' in the 1960s.

In 2002, a team led by geneticist Makoto Matsuoka at Nagoya University in Japan discovered[5] that IR8 owed its short stature to a loss-of-function mutation of the semi-dwarf gene *sd1*. The group found that the genetic impairment led to defects in the biosynthesis and signalling pathways of gibberellin, the plant hormone responsible for controlling cell elongation. The cells were shorter, but in all other respects functioned normally.

Scientists are also targeting the genetic basis for other crucial aspects of rice production.

Research into rice genetics is looking to minor genes to make small, accumulative improvements to yield.

"There are three key elements in grain yield: panicle size, grain number and grain size," says Jiayang Li, CAAS project director and a driving force behind the 3,000 Rice Genomes Project. "A rice plant in which these components are great would naturally have high yield."

In 2003, Li and his team identified a gene called *MONOCULM 1* (*MOC1*) that functions as the master control for shoot development[6]. They showed that rice plants that overexpress *MOC1* produce more auxiliary stems that branch out from the mother stem than normal, whereas those with a loss-of-function mutation in *MOC1* produce only a single, stout stem. Li now aims to find the right expression level for *MOC1* to decrease the number of stems while increasing the number of seed-bearing branches, which could lead to even more impressive yields. "Then the grains can become larger and heavier, thus the grain yield further improves," he says.

In theory, scientists could use genetic engineering to ensure that all rice breeds carry the most useful, high-yielding mutations. But it is not that simple. One potential obstacle is the widespread public opposition to genetically modified crops, but there are also many technological challenges to overcome. The *MOC1* gene is a case in point: the loss-of-function mutation not only impairs the proliferation of stems, it also increases plant height and reduces the number of panicles. These unintended consequences are a reminder that grain yield is a complex agronomic trait controlled by not one but many regions of DNA. Moreover, most of the genes known to have a beneficial effect on yield have already found their way into common strains, limiting their ability to increase rice yield further.

If scientists are to revolutionize rice production, they may have to search for wild varieties that have rare gene variations. There is a precedent for this approach. In 1996, geneticists Pamela Ronald at the University of California, Davis, and David Mackill at IRRI set out to find a wild variety of rice that was particularly tolerant of flooding. A decade later they identified[7] a cluster of three genes that is responsible for submergence tolerance, the ability to survive after being under water for two weeks. Researchers at IRRI — led by Mackill and plant breeder Abdelbagi Ismail — used precision breeding to introduce the key gene from the cluster into a strain from Bangladesh, where rice is particularly prone to flooding. Early trials showed that the flood-resistant gene improved yield by up to sixfold in some areas. The modified plant is now widely grown in other flood-prone countries, including India and Indonesia.

MINOR GENES AND MAJOR BENEFITS

Most investigations into the genetics of rice production have focused on genes that have a great effect on productivity. But such big-ticket genes don't tell the whole story. "Although each of these genes may improve yield by 3–5%, there are also hundreds of minor genes that can improve yield on a much smaller scale, say 0.5%," says geneticist Bin Han at the National Center for Gene Research of the Chinese Academy of Sciences in Shanghai.

Identifying these minor genes requires next-generation sequencing technologies and genome-wide association studies[8]. But once that is done, it raises the prospect of stacking minor genes together to improve the yield under a wide variety of conditions. "Within the next ten years, a breakthrough technology will emerge and we can begin using these minor genes in improving grain yield," Han says.

In Han's view, harnessing these minor genes is one more step towards a more productive future. Just as the plants of the early 1960s seem fragile and unproductive by today's standards, so the crops of coming decades may far outshine anything grown today. "I think we are on the edge of the next green revolution," he says. ■

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