Tillers of the Soil

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When you sip a perfect cup of coffee, you probably aren't thinking of the multitude of genes that had to turn on and off in the right order to ensure that the tree that produced the fruit that produced the beverage you're drinking had everything it needed to deliver such perfection—but someone was....

The day's marathon of meetings was over and it was dark outside. I had just ordered a cold Pilsner from the hotel bar and headed out to the patio to find my colleagues, the renowned coffee breeder Benoit Bertrand and coffee geneticist and World Coffee Research's Scientific Director Christophe Montagnon. When I finally spotted them, they were hunched over a laptop, their faces lit by its glowing screen, talking excitedly in French. Dr Montagnon was pointing to a particular cell on a huge spreadsheet arrayed in coloured patterns. Dr Bertrand leaned in, nodded his head with a goofy excited-kid smile, sat back in his chair, and took a long, satisfied glug of beer.

'What are you guys up to?' I asked, reluctant to disturb their reverie.

Dr Montagnon looked up, rearranged his body to face me, and he appeared to be trying (unsuccessfully) to suppress a huge smile from splitting across his face. 'We think we have just confirmed the molecular marker for Coffee Berry Disease resistance,' he said. The disease devastates African coffee farms—a 1968–69 epidemic led to the loss of 50 per cent of Kenya's coffee crop; spraying for the disease can make up as much as half of an estate's production expenses. Coffee breeders have been working to create new CBD-resistant varieties since the 1970s, but the work is long and arduous. It can take 30 years to create a new variety. A genetic marker had previously been identified for CBD resistance, but it had never been verified against a database of all arabica varieties—meaning no one was really sure if it could be used by breeders to accurately predict CBD resistance.

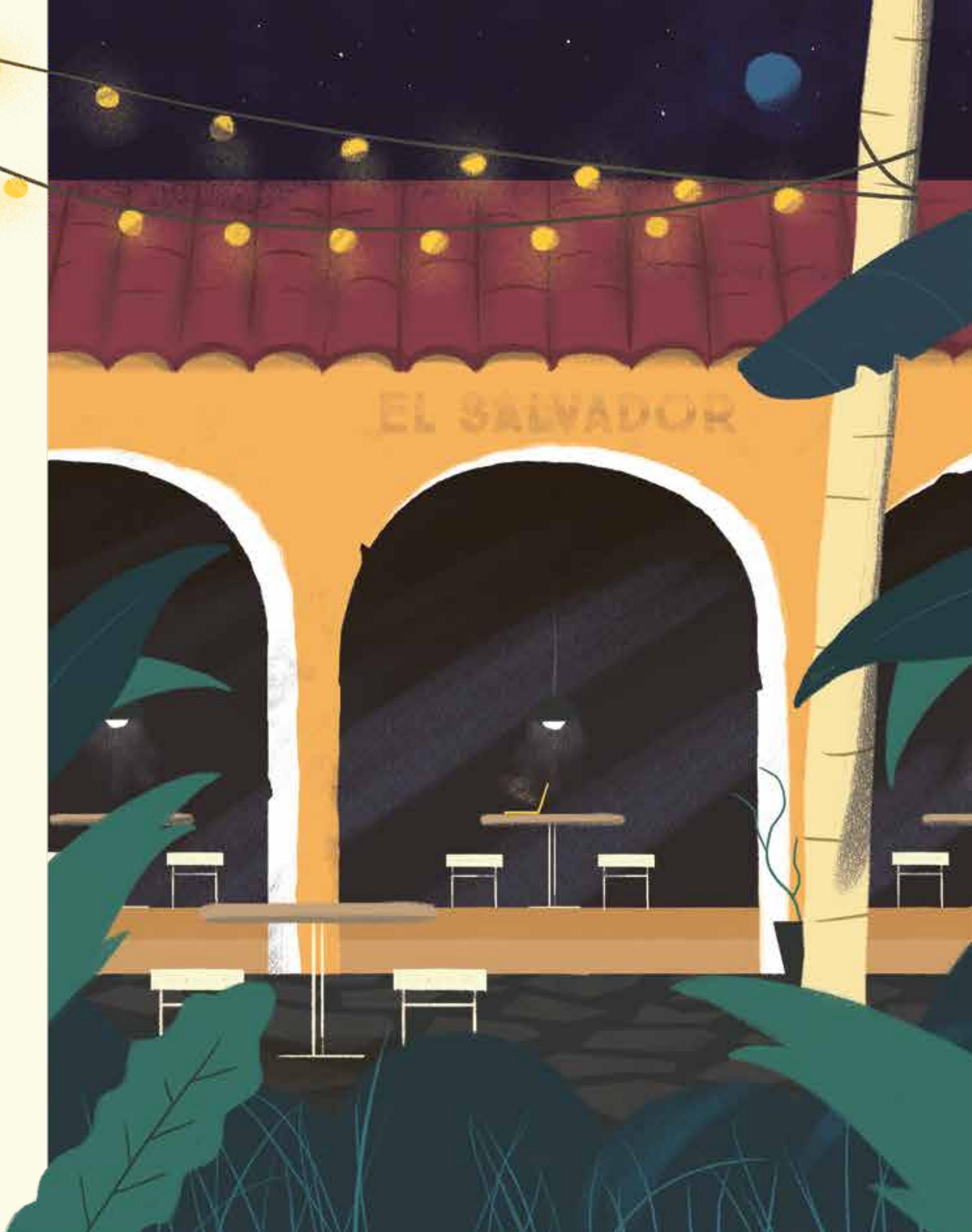
'Just right now?' I asked. 'Like, just right this minute?'

'Just right this minute,' he replied. And then he did a thing all scientists develop early proficiency in: hedge. 'I mean, we need to verify; there is still more work to be done...' But as he trailed off, his smile broadened.

The good doctors were trying hard to be cautious, to reign in premature enthusiasm, but they were pretty sure: they had just made an essential discovery in modern applied coffee breeding. This called for a little ritual celebration, an acknowledgement of their work and the work of those who had paved their way. I marched back to the bar and ordered a round of the best whisky they had—the only one on the top shelf, Johnny Walker Blue. I folded up the $300 receipt carefully and tucked it in my bag. I planned to show it to my daughter one day.

BREEDING IN THE 20TH CENTURY

A coffee breeder of 100 years ago could not have imagined this scene (molecular marker? laptop?!). The earliest breeding work was basic selection of



naturally occurring variants of plant species—different varieties, the embodiment of genetic variation—that had desirable traits. A breeder's work was informed primarily by observation: observe the problem, and then seek out and select variants that address it.

For nearly all human agriculture, the main problems, besides the vagaries of weather, have been disease and pests. Early 'breeders'—often just perceptive farmers—observed that some varieties were more tolerant than others to key coffee diseases. Around 1920, two nearly simultaneous observations made on two farms half a world apart changed the course of coffee breeding history—and thus, of coffee.

Sometime between 1915 and 1918, on a plantation in Minas Gerais, Brazil, someone noticed an aberrant plant. It was very similar to the Bourbon-variety plants around it except in one key attribute: it was short and squat instead of tall and lanky. The plant had a naturally occurring, single-gene mutation that causes the plant to grow smaller ('dwarfism'). Local farmers quickly realized they could plant the variety more densely, thus increasing the amount of fruit produced per hectare. Because it was short, it was also easier to harvest. The variety came to be known as Caturra. After Caturra's discovery, selections were made by the Institute of Agronomy (IAC) in Campinas, Brazil, starting in 1937. It remains one of the most important varieties in the Americas, and is still widespread across South and Central America.

Meanwhile, 16,000 kilometres away on the island of East Timor, another profoundly important genetic event—one that should have been impossible—was unfolding. Two coffee plants of different species, *Coffea arabica* and *Coffea canephora* (popularly called robusta), were having sex. The resulting love-child was perhaps the most famous single coffee plant in history: the Timor Hybrid. This interspecific hybrid was, genetically, an arabica plant (meaning it could reproduce with other arabicas), but it had received a profound gift from its robusta parent—genes conferring resistance to coffee leaf rust.

In 1958 or 1959, the Centre for the Investigation of Coffee Rust (CIFC) in Portugal, famous for its research into coffee leaf rust, received some Timor Hybrid seeds from the island of Timor. In 1967, breeders in Portugal began work to create new cultivars that would be resistant to the disease, but also have a compact stature allowing denser planting. Multiple crosses between rust-resistant Timor Hybrid plants were made with the dwarf Caturra variety and a similar Bourbon-mutant variety discovered in Costa Rica in the 1960s called Villa Sarchi. The resulting crosses were dubbed 'Catimor' and 'Sarchimor'.

After some initial testing in Brazil, in 1971 CIFC sent the early crosses out for field trials in experimental centres in several countries across Asia and the Americas. Subsequent selections of the crosses yielded the first modern wave of new coffee varieties, all dwarf and rust-resistant. This was coffee's 'green revolution'—a new wave of varieties meant to maximize yield through higher planting density and resistance to a major production-killing disease. They were disseminated around the world, finding firmer foothold in some places than others.

The solution turned out to be one that required a significant compromise from coffee producers. While breeders had been relentlessly focusing on helping farmers increase production and reduce the harm from disease, the coffee market was slowly—then quickly—turning its attention to cup quality. At almost the exact moment that the new leaf rust-resistant varieties were being released to farmers in the '90s, the specialty coffee movement was getting underway and new buyers, by and large, didn't like the new varieties. This forced producers to make an impossible choice: keep the old varieties that had market-pleasing cup quality, but risk massive losses, or replant with newer varieties that could alienate higher-paying buyers. Starting in 2007 in Colombia and then spreading to Central America in 2012, the worst happened. A devastating epidemic of coffee leaf rust that wiped out production on farms with the old varieties. For many producers, the economic shock was too much to bear, and they lost or sold off their farms. The resulting impact to farmworkers who could no longer find employment picking coffee forced a wave of human migration that led in part to the major uptick in unaccompanied minors fleeing to the United States.

In one sense, the efforts of 20th-century coffee breeders were a triumph. Breeders had spent 50 years preparing for a rust epidemic, and they were ready when it came. Despite widespread impact, it surely would have been orders of magnitude worse if the new varieties hadn't been available at all. But looked at another way, those efforts look bleaker, and seem to rely on a heavy dose of historical luck. The Catimor and Sarchimor varieties began to be released for farmers in the early 1990s, *more than 70 years* after observation of the special characteristics of the Timor Hybrid and Caturra. It was more than 30 years after intensive breeding with modern field evaluations had begun. This is largely the unfortunate (from a breeding perspective) result of coffee's status as a perennial tree crop—it takes three to five years to mature. If you need to conduct multiple generations of selection, this stretches the time it takes to create new varieties to over 20 years, sometimes as many as 40.

BREEDING BETTER

Can modern genetics help us respond to farmers' needs more efficiently? That is the principle question today's coffee researchers are asking, including Dr Bertrand and Dr Montagnon at World Coffee Research. Ideally, the time it takes breeders to identify desirable traits and then work those traits into new varieties would be far shorter than 70 years or 30 years. It would ideally be no more than 10. Given the many challenges coffee producers face, even that feels like a difficult compromise.

Is it possible? Maybe. First, you must identify the traits you're looking for—much trickier than you might think with complex characteristics like cup quality or drought tolerance—and then develop a way to rapidly and cheaply determine if those traits are present in a large number of plants without having to wait for the three to five years it takes for the trees to mature.

In an article in *Scientific American*, Ed Buckler, a plant geneticist at Cornell University, explains: 'We know that old-fashioned good breeding works … and a lot of that is an intelligent numbers game' based on genetic theories elaborated by Gregor Mendel more than a century ago. Molecular breeding, he added, 'is now a way to do that much faster.'

And in fact, this is exactly the promise of modern molecular breeding. The approach allows breeders to use genetic information to predict what a plant or cross will do and to make predictions based on DNA profiles of plants using molecular markers associated with a trait, such as fruit shape, rather having to wait to observe the trait itself. It's the difference between being able to take a DNA sample from a baby plant in a nursery at six weeks versus waiting three or more years to see if the trait emerges. In short, it's a way to do what old-fashioned breeders did, but much more rapidly. Once a desired marker is identified, it can be followed through the generations, helping breeders ensure that traits of interest are carrying through. By cutting out all the waiting-around-and-seeing, it can cut the time and cost to select or obtain new varieties in half—or more.

Many new plant varieties—including foods you have seen at the grocery store—have been created this way. Famous examples include 'scuba rice' that can survive more than two weeks of flooded conditions, wheat that resists the advance of devastating aphids, snack-size bell peppers, and 'heatless' habaneros. With little fanfare, at seed companies like Monsanto, Pioneer, and Dow, molecular marker assisted breeding is rapidly becoming the norm.

It's easy to see why. The approach exploits the advances of the 'genetics revolution' to create sometimes-dramatic new possibilities, and it can do so without the stigma of genetic modification. 'The impact of genomics on plant breeding is almost beyond my comprehension,' Shelley Jansky, a potato breeder at the University of Wisconsin-Madison told *Scientific American*. She describes how, eight years ago it took a graduate student three years to identify just 18 genetic markers associated with potato disease resistance. By 2014, they could locate 8,000 markers within a matter of weeks.

Despite using modern genetic data to speed up breeding, the breeding itself can still happen the good old-fashioned way—just a breeder with a paintbrush, transferring pollen from plant to plant, maybe with a little mood music in the background.

IS IT REALLY A REVOLUTION?

Despite its promise, molecular breeding is far from a panacea. It's applicability for coffee is still almost entirely theoretical. Only a tiny handful of markers for traits that could be meaningful for coffee producers have been identified. As of yet, *none* have actually been used to create a new variety. (That may soon change with the identification of a universally applicable marker for CBD-resistance.) In genomics, as elsewhere, coffee lags sorely behind other crops.

But perhaps most importantly, marker-assisted selection can't be used for complex traits like cup quality. Marker-assisted selection only works for traits controlled by single genes, or very small numbers of genes (called monogenic or oligogenic traits). Researchers assume that complex traits like cup quality are controlled by dozens or even hundreds of genes interacting in complex ways with each other and with the local environment (called quantitative polygenic traits). In coffee, some promising 'simple' traits include male sterility, which allows F1 hybrids to be propagated by seed instead of in expensive tissue culture labs; dwarfism; and white stem borer resistance. But what about cup quality, disease resistance, heat and drought tolerance, adaptation for agroforestry? These are arguably the most important characteristics for breeders to focus on in the 21st century, but seemingly the furthest out of reach of marker-assisted selection.

But breeders are increasingly excited about another molecular breeding approach. It is called genome-wide selection, and it can target polygenic (e.g., complex) traits. Breeders don't look for the presence or absence of one or two genes; they look for the presence or absence of a set of thousands. In effect, it's a black box—breeders have no idea what each gene or marker does, only that the combination results in the desired trait. The approach has been successfully used in cow breeding. The potential for arabica coffee, however, is far from being realized. It will take years of research, observation, and sequencing to develop a database of useful genetic linkages to desired traits. And the persistent lack of funding for advanced coffee R&D doesn't help the work along.

IF IT MAKES SENSE

Molecular breeding holds terrific potential, and many researchers around the world are chipping away at the edifice of arabica genetics. But it's far from a cure-all: will it give the right bang for the buck? To justify the cost of marker-assisted selection, you need good markers that accurately predict desirable traits more cheaply and efficiently than existing methods. In short, coffee breeders will use marker-assisted selection and quantitative breeding *if it makes sense* to do so, meaning if it delivers a high enough return on investment, measured as genetic progress against time saved and money invested. Truthfully, we don't know how much sense it will make for coffee right now—the work is only just beginning.

Still, researchers at World Coffee Research and elsewhere are already availing themselves of some of the thrilling developments of the genetics revolution. For example, we can now use genetic markers to test what variety an arabica coffee tree is, something we use in WCR Verified, a programme to certify coffee nurseries and ensure that farmers are receiving the correct variety. And we are using genetic sequencing data that tells us the 'genetic distance' between two varieties (e.g., how genetically dissimilar they are). This allows us to make new F1 hybrid crosses that maximize 'hybrid vigour', which comes from crossing two parents that are genetically far apart from one another. We can't be sure what traits the offspring will have—we will still have to do the long, expensive work of field observations—but the approach is allowing us to incorporate novel genetic diversity that has never been used before in coffee breeding.

The tools of the modern coffee breeder are a mishmash of the old and the new—paintbrush, laptop, field boots, machines that shear DNA into fragments. Discoveries are as likely to be made hunched over a laptop on a hot night in El Salvador as they are in the field. And that is for the best. Good, old-fashioned breeding works. But modern genetics offers us new ways of making the work more responsive to the needs of coffee farmers.

To learn more, take a look at the WCR website.