But GT Sophy's success on the track suggests that neural networks might one day have a larger role in the software of automated vehicles than they do today.

So, will the Formula 1 battles between Lewis Hamilton and Max Verstappen give way to contests between GT Sophy variants? After all, the physics of *Gran Turismo* is a close match for real racing cars. *Gran Turismo*'s director, Kazunori Yamauchi, even used the video game to find ways of tweaking his real racing car to overcome a recurring problem that he was having when taking a corner at the Nürburgring, a Grand Prix track in Germany that has the nickname The Green Hell (see go.nature.com/3tw22aa). It also helped me to familiarize myself with Laguna Seca Raceway before I started racing school.

Still, some challenges remain in moving from the console to the track. For example, GT Sophy has not yet learnt that it is sometimes better to follow the car ahead to make up time, instead of dogfighting at every corner. Of course, Wurman *et al.* report GT Sophy's rookie season, and there is no obvious reason why such a strategy could not be learnt with greater experience, too.

More challenging might be the variation that occurs with each lap. Unlike in the *Gran Turismo* races used by Wurman and co-workers, the condition of the tyres on real racing cars changes from lap to lap, and human drivers must adapt to such changes throughout the race. Would GT Sophy be able to do the same with more data? And where would such data come from? It's easy to run simulations, but no racing car in existence has completed enough laps to train GT Sophy in its current form, much less an AI that could handle tyre variability. However, there is evidence that neural networks can capture changing vehicle dynamics on different road surfaces[2], so perhaps Verstappen and Hamilton should keep one eye on their rear-view mirrors.

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Plant sciences

Hard graft problem solved for key global food crops

Colin Turnbull & Sean Carrington

Grafting has long been used to join tissues of different plants in horticulture and research. Methods have now been devised to extend the technique to plants called monocotyledons, which include major crops such as cereals and bananas. **See p.280**

The technique of grafting together the shoot of one plant and the roots of another is immensely beneficial in a variety of contexts. However, efforts to use this approach have long failed for certain key crops. On page 280, Reeves *et al.*[1] report success in developing a grafting method that can be used for plants called monocotyledons, or monocots.

Plant grafting has an ancient history, dating back to early civilizations. More than 2,000 years ago, *De Agri Cultura* ('On Farming'), a book written by the Roman senator Cato, details the grafting of vines and fruit trees, indicating it to be commonplace. Such grafting practices remain widespread today.

Yet one major group of plants, the monocots, have proved problematic for use in grafting. The name refers to the single leaf (a cotyledon) in the plant seed, a feature that distinguishes monocots from other flowering plant groups that have two cotyledons, and that are conventionally called dicotyledons, or dicots. Monocots abound in the global flora. They include all of the world's cereals – rice, wheat and maize (corn) – which together provide more than half the calories consumed by humans. Another key monocot is the banana, a staple food in many nations and the world's most popular fruit after the tomato.

Despite many attempts to graft monocots, minimal success meant that grafting never became mainstream. Indeed, many experts viewed monocot grafting as a near-impossible feat[2,3], often attributing failure to anatomical differences between monocots and dicots, especially monocots' lack of a specialized inner cellular layer found in dicots called vascular cambium. However, paradoxically, there are witchweeds – dicot plants of the genus *Striga* that live as devastating parasites attached to the roots of monocot crops such as maize and sorghum[4]. The parasite feeds through an interface that is, in essence, a natural graft plumbed into the host's transport (vascular) systems, proving that nature long ago accomplished a version of grafting that humans have struggled to achieve.

Reeves and colleagues present compelling evidence that monocot grafting is feasible, after all, and propose that the absence of vascular cambium is not a limiting factor. Instead, their work focuses on a feature shared by all plants: immature tissue that can be reprogrammed to make the essential connecting structures needed for a successful graft. The authors' use of fine surgical tools enabled the precise assembly of grafts of young germinating seedlings at a time in the plants' development when the root is just emerging, whereas the same method tried in older plants proved much less successful.

One key to plants' terrestrial dominance is linked to their extraordinary ability to recover from damage, whether arising from storms, herbivore grazing or simply humans mowing the grass. With a much greater regenerative capacity than that of most vertebrates, many types of plant cell are totipotent, enabling the replacement of missing parts. Sometimes, this regenerative process requires the formation of a disorganized group of cells called a callus, from which tissues and organs emerge. In grafting, when two cut pieces are placed together, a wound-repair mechanism makes connections between the pieces, resulting in a new whole plant. An essential feature of this process is connection of the plant's 'plumbing system' – the vascular highways of tissues called xylem and phloem that transport water, sugars, nutrients and other molecules throughout a plant (Fig. 1).

Reeves *et al.* report that, within days of making a monocot graft, they observe fluorescent dyes (applied to the cut surface) moving in both directions across the graft. Vascular cells develop, and the graft is sufficiently strong to be picked up by hand.

The authors find that genes in cells around the graft junction are rapidly expressed, as a prelude to visible signs of graft formation. The expression of many of these genes is a hallmark of regenerative processes. The genes encode wound-repair factors, regulatory proteins and hormones, as well as components needed to

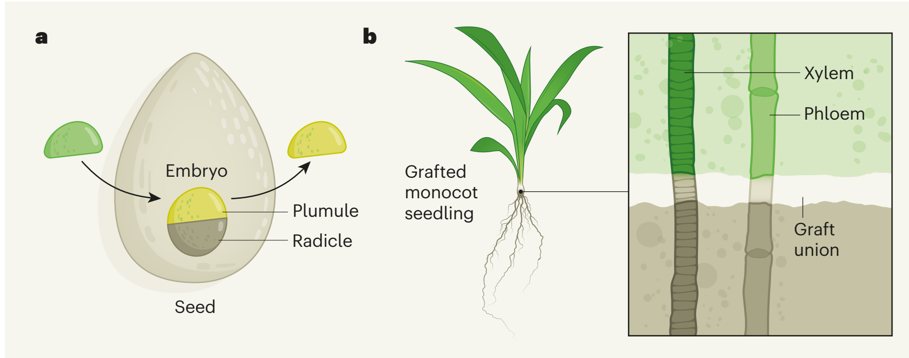

Figure 1 | Grafting of crop plants. Plants called monocotyledons, or monocots, include cereals and many tropical crops. Grafting of monocots – the production of a plant that has roots and shoots from different plants – has a history of failure. Reeves *et al.*[1] report a successful monocot grafting method. **a**, This approach in cereals uses germinating seeds. The embryonic shoot (called the plumule) is excised and replaced by a plumule from a donor seed, ensuring that transplanted material makes close contact with the radicle (the embryonic region that forms the root). **b**, Immature cells at the interface of the grafted tissue, called the graft union, reprogram to join up the two parts. Communication and the movement of materials (such as water and nutrients) between the shoot and the root was possible because the xylem and phloem tissues of the transport system connected. Grafting offers a way to engineer plants that have beneficial characteristics, such as those aiding their ability to cope with diseases and stresses exacerbated by climate change.

restart the cell cycle and cell growth, remodel cell walls and create the essential vascular connections. Some of the gene-expression patterns observed by the authors mirror those seen during graft formation in dicots[5], whereas others might be unique to monocots.

Intriguingly, Reeves *et al.* report that grafts could be made between strikingly different pairs of cereals, such as between wheat and sorghum, that cannot generate a hybrid offspring plant through a conventional pollination approach. The authors explored a spectacular spectrum of edible and ornamental monocots, examining the sorts of plant that can be found by raiding the shelves of garden centres and tropical greenhouses. From palm to pineapple, agave to lily, cardamom to yam, all yielded grafts through cutting and connecting young seedlings.

Banana proved amenable, even though most cultivated varieties do not make seeds. To succeed with this fruit, Reeves and colleagues grafted microscopic banana shoots grown in laboratory cultures to genetically different roots. These rapidly developed into normal-looking banana plants. Given that the world's most popular banana, a variety called Cavendish, is at risk of being wiped out by the fungus that causes the deadly Panama disease, or banana wilt[6], grafting bananas onto disease-resistant roots might present an opportunity to combat this threat. Indeed, wheat plants readily succumb to the soil fungus that causes an infection called take-all disease, but Reeves *et al.* found that the plants were protected if wheat shoots were grafted onto disease-resistant oat rootstocks.

Similar approaches to tackle plant disease already exist for dicots. For example, in the nineteenth century, grapevines were devastated by the insect pest phylloxera. Grafting saved the day back then, and most grapes cultivated worldwide continue to be grown on phylloxera-resistant rootstocks[7]. For monocot root crops such as yam, where high-yielding varieties might be limited by shoot susceptibility to disease, grafting of plants to disease-resistant shoots could be a game-changer.

Reeves and colleagues' demonstration that grafting is feasible in monocots opens the door to the investigation of many questions for research, some of which have been explored only in dicots. Previous grafting work has already led to insights into how different parts of a plant communicate with each other. Moreover, grafting offers a way of altering plant development, such as accelerating the start of flowering[8], changing plant height[8] and modifying the number of branches. With regard to branching regulation, Reeves and colleagues confirmed that monocot roots transmit the same signals as those used by dicots, with grafted roots being able to suppress branching of mutant shoots that lack the ability to make the branch-inhibiting hormone strigolactone[9,10]. Optimizing the number of stems or branches on a plant is valuable in agriculture. Too few can mean low numbers of the flowers that develop into grains or fruits, but too many create crowded, spindly, unproductive shoots.

Grafting can reveal the types of molecule that travel through the plant vasculature. For example, when a disease-causing agent invades a leaf, local defences are activated, and signals might then travel to the rest of the plant, providing a spreading immunity that provides protection ahead of further attacks. Antimicrobial metabolite molecules can move across graft sites, as can many defence and stress hormones, and other larger signalling molecules, such as RNA, peptides and proteins[11].

It might not be possible for grafting to be adopted across the millions of hectares currently devoted to cereals – it would be impractical to graft every seedling before it is transplanted into fields. But there could be huge benefits in grafting high-value crops and longer-lived species such as palm trees, analogous to the widely deployed use of grafting of dicot tree fruits, vines, melons and tomatoes. Grafting could offer a way to develop specialized root systems tailored to local challenges from pests and diseases. Alternatively, it could help plants to cope with drought or adapt to soils that lack nutrients or have high levels of salt. Climate change and certain forms of intensive agriculture are exacerbating many such problems.

Grafting might be superior to using conventional breeding to introduce stress-response factors into elite plant varieties. This is especially pertinent if the factors originate from wild undomesticated relatives, because the unpredictable mixing of genomes through conventional breeding often leads to compromises in the quality and quantity of crop production.

The next few years should see the refinement and expansion of monocot grafting. This should pave the way for the technique to become commercially viable. Monocot grafting would add a new weapon to the armoury that could enable plants to remain robust in the face of the many pressures that climate change will continue to exert on the planet's ecosystems.

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