AVs that may reflect shared intra-host dynamics (Supplementary Fig. 1 and Supplementary Table 2). It can also highlight the emergence of mutations interfering with binding of polyclonal antibodies[9] (for example, COG-UK data in Supplementary Fig. 2), suggesting possible intra-host dynamics. These and other interactive notebooks and dashboards on the platform could identify AVs that warrant closer monitoring as the pandemic continues.

Our system is designed to encourage scalable collaborative worldwide genomic surveillance to identify and respond to emerging variants. By relying on raw read data rather than assembled genomes and allowing every result to be traced back to its raw data, it goes a step beyond current surveillance efforts. Specifically, it enables surveillance of intra-patient minor AV frequencies—a distinction that could yield early warnings of epidemiological conditions conducive to the emergence of variants with altered pathogenicity, vaccine sensitivity or drug resistance. ❐

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Published online: 29 September 2021
https://doi.org/10.1038/s41587-021-01069-1

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Acknowledgements
The authors are grateful to the broader Galaxy community for their support and software development efforts. This work is funded by NIH grants U41 HG006620 and NSF ABI grant 1661497. Usegalaxy.eu is supported by the German Federal Ministry of Education and Research grants 031L0101C and de.NBI-epi to B.G. Galaxy and HyPhy integration is supported by NIH grant R01 AI134384 to A.N. Usegalaxy.org.au is supported by Bioplatforms Australia and the Australian Research Data Commons through funding from the Australian Government National Collaborative Research Infrastructure Strategy. The hyphy.org development team is supported by NIH grant R01GM093939. Usegalaxy.be is supported by the Research Foundation-Flanders (FWO) grant I002919N and the Flemish Supercomputer Center (VSC). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41587-021-01069-1.
Peer review information *Nature Biotechnology* thanks Jason Sahl for their contribution to the peer review of this work.

Rapid delivery systems for future food security

To the Editor — The current world population of 7.8 billion is predicted to reach 10 billion by 2057 (https://www.worldometers.info/world-population/#pastfuture). Future access to affordable and healthy food will be challenging, with malnutrition already affecting one in three people worldwide. The agricultural sector currently provides livelihoods for 1.1 billion people and accounts for 26.7% of global employment (https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS). However, our reliance on a small number of crop species for agricultural calorie production and depletion of land, soil, water and genetic resources, combined with extreme weather events and changing disease/pest dynamics, are already jeopardizing future food security[1]. Climate change–induced reductions in the global yield of major crops (for example, rice, wheat, maize and soybean) are more pronounced in low-latitude regions and thus affect farmers in developing countries[2]. As is evident from temperate cereal crops, a robust seed system that delivers improved cultivars to replace old cultivars is a plausible approach to adapting agriculture to climate change[3]. Here we provide an overview of how seed input supply systems and new production and harvesting technologies can generate increased incomes for developing world farmers and deliver better products to consumers.

Crop improvement remains crucial to the United Nations' Sustainable Development Goal 2 (SDG 2) of 'Zero Hunger: ending malnutrition and achieving food security by 2030'. It offers sustainable solutions for food production and food security by creating high-yielding, nutritious crops that can withstand emerging biotic and abiotic stresses. Innovative crop breeding techniques that accelerate the breeding cycle (for example, speed breeding[4]), facilitate more precise genetic combinations (for example, genomic selection[5]) and enable precise genetic changes (for example, genome editing[6]) provide unprecedented opportunities for enhancing crop performance in controlled conditions and research plots[7]. Translating crop productivity gains from experimental settings to real-world farming conditions requires improving equitable access to innovative technologies for all farmers and providing legislative, economical and practical support to ensure their adoption[8].

After the development of better-performing varieties, several steps are required to realize higher crop yields and income for smallholder farmers and deliver enhanced agricultural outputs (Fig. 1). The integration of planting good-quality seeds of elite crop varieties with improved decision support tools, mechanical harvesting and post-harvest management will increase production gains. Electronic trading portals (for example, Wefarm (https://about.wefarm.com/), eNAM (https://www.enam.gov.in/web/) and Digital Mandi (https://www.iitk.ac.in/MLAsia/digimandi.htm)) and support from farmer associations should help farmers market their produce directly for fairer prices. Further processing and addition of value can also deliver improved products to consumers and increase farmer's income (Fig. 1).

Seed is the single entry point for crop resilience and productivity. The sustainability of crop production is vitally dependent on the timely supply of improved seed and other inputs. In developing countries, formal seed supply systems generally do not meet farmers' demands, such that smallholder farmers source more than 80% of their seed from

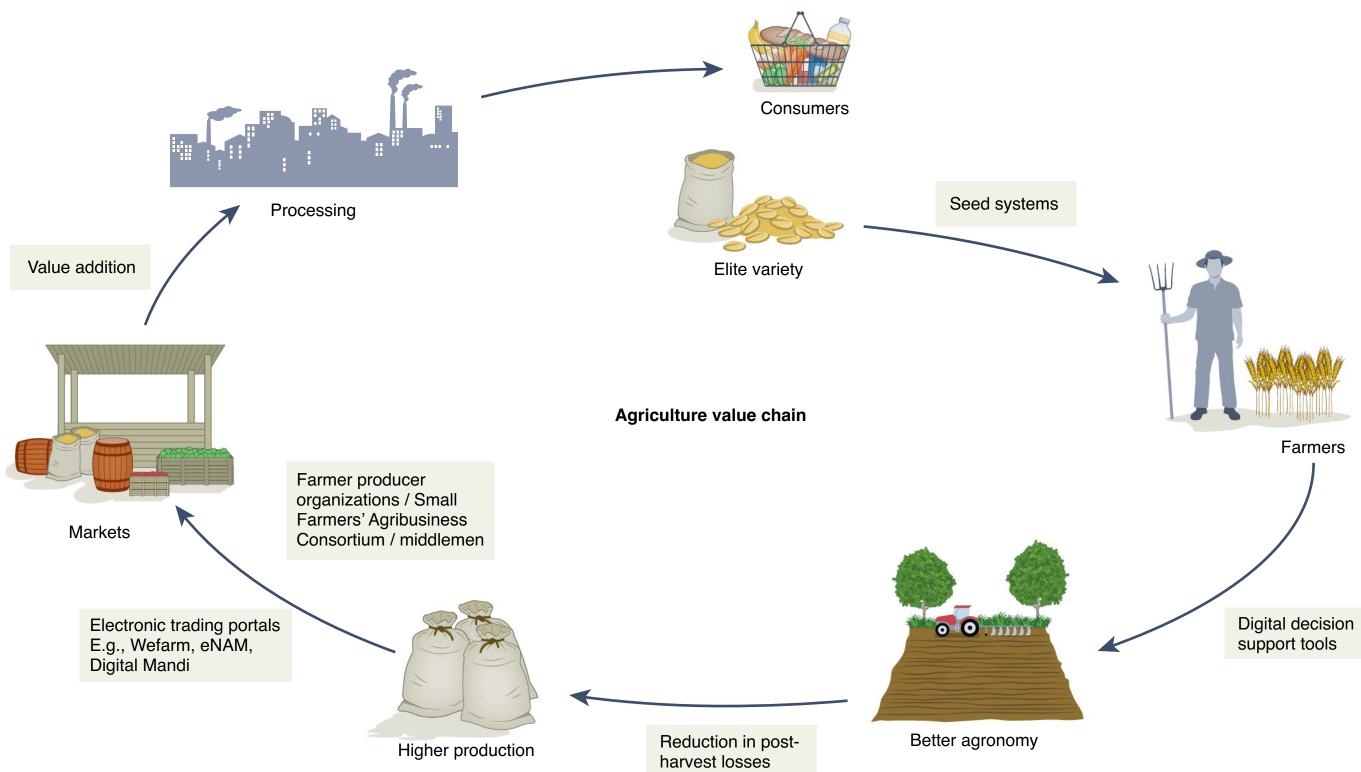

Fig. 1 | Rapid delivery of new cultivars to farmer fields and better products to markets. New crop products developed through innovative breeding technologies should be accessible to farmers. Improved seed and the input supply system remain at the core of farmer accessibility needs. Equally important will be better crop production technologies based on site-specific packages. Institutional support from the public sector (for example, digital agriculture tools, computational decision and analytics tools or digital communication tools) can contribute substantially to this end. Mechanized harvesting and more widespread cold-storage facilities could also reduce harvest losses. Value addition to farm produce could increase farm income, diversify production and provide new markets.

informal seed systems. Some South Asian countries, such as Nepal, ensure seed supply through community-based seed banks[9], but most of the seed is not from elite varieties, which limits productivity and reduces environmental resilience. Promoting elite varieties, linking farmer seed producers with public sector breeding programs, and making seed available through key extension agents and farmers will improve access to the most suitable seeds. Participatory breeding and on-farm testing of improved crop varieties will increase smallholder adoption of this approach. The timely supply of agricultural inputs at affordable prices can also substantially improve yields. Private sector involvement in seed and input supply systems has increased crop yields (for example, that of maize) in many South Asian and African countries. The supply of quality seed of improved cultivars and other inputs (for example, fertilizer) by private entities and government institutions increased yields by 68–97% from 2008 to 2012 for progressive farmers in some parts of China and 62–80% across the whole country[10].

Boosting crop productivity in farmer's fields calls for the adoption of better crop production technologies. Site-specific packages for crop production need to integrate agronomic components according to site, area and conditions to enhance yield, conserve natural resources and protect the environment[11]. Seeding rate and planting time are critical components of crop production packages, but they vary between locations. For instance, in China over-seeding of wheat reduced potential yield by 6.3% and under-seeding of maize reduced potential yields by 20.6%; meanwhile, timely sowing increased yields by 6.3% for wheat and 15% for maize. Timely irrigation and fertilizer application reduced wheat yield losses by 6.2%, whereas maize yield increased by 7.5% and wheat by 11.6% following recommended fertilizer regimes[10]. Integrated nutrient management incorporates optimal nutrients from various resources and synchronizes crop demand and supply. Using innovative nutrient-specific strategies such as urease inhibitors, fertilizer incorporation at depth and coated urea could improve nutrient use efficiency and crop productivity. Integrated pest management involving innovative ecological pest management strategies could help manage agricultural pests. Under rain-fed conditions, the use of mulch (for example, crop straw, plastic or gravel sand) can preserve soil moisture and increase moisture availability to crops. In China, ridge–furrow plastic mulching of maize increased water-use efficiency by 70% and improved nitrogen-uptake efficiency by 45%, relative to flat irrigation[12].

Institutional support and digital agriculture are pivotal for improving agricultural productivity. The most effective way to increase yields is through improved seed and fertilizer use and institutional support from the public sector. Input subsidies could be an option in this regard. In Malawi, maize production doubled in 2006 and almost tripled in 2007 through a national input subsidy program[13]. Improved access to fertilizers by state-supported subsidies, rural credits and improved infrastructure has helped virtually double the average yield of wheat and rice in Asia (https://www.un.org/en/chronicle/article/agriculture-leads-mdgs-rural-development-africa).

Agricultural extension methods increased wheat and maize yields in China through three means. First, they raised awareness through field demonstrations, farming schools and yield contests. Second, they provided information in posters and calendars. And finally, they engaged farmers via in-person communication and social-cultural bonding with on-site advice and reminders at critical times[10].

Digital agriculture tools (for example, geographical information systems, global positioning systems, remote sensing, yield monitors, autosteered and autoguided equipment, unmanned aerial vehicles, variable-rate technologies, computational decision and analytics tools, and digital communication tools) have led to substantial productivity improvement in modern cropping systems. This is achieved by the generation of high-resolution soil maps, real-time crop monitoring, precision input application that improves resource use efficiency and reduces yield loss due to soil and agronomic inconsistencies. By generating large quantities of data of near-research standards, such digital tools not only assist in aligning agronomic research closer to farmers' needs, but also may better inform agricultural policies.

Educating farmers about harvest and post-harvest losses, and ways to minimize these losses, is paramount as ~30–40% of crop yields (perishable and grain crops) worldwide are lost after harvest, primarily through the lack of mechanized harvesting and limited cold-storage facilities. For example, in Southeast Asia, about one-third of rice is lost after harvest (http://www.fao.org/News/FACTFILE/IMG/FF9712-e.pdf). Reducing these losses requires improved market access[14], the promotion of mechanized crop harvesting and threshing, construction of grain storage facilities, and efficient storage technology. Marketing is a key deciding factor for crop choice by farmers. Inadequate transport systems and market infrastructure can substantially increase input costs (for example, seeds, pesticides and fertilizers) and hinder input availability[15]. Strengthening the market system with government rules and regulations and improving market access from field to market with more road infrastructure should increase farmers' profit margins. Although intermediaries help link producers and the consumers, they usually take the major profit share. Alternative marketing strategies (for example, direct, contract and group marketing or futures trading) could help farmers increase their profit.

Adding value to agricultural commodities increases their economic value and consumer appeal. Precision cleaning, grading, drying and attractive packaging should increase the value and market price of farm produce. Processing food grains and other crops into non-traditional food and non-food products could also add more value.

In our opinion, the full potential of improved crop varieties can be realized by strengthening seed systems, integrating better agronomy and digital tools, reducing post-harvest losses and providing market access to farmers. The benefits of these technologies must be distributed equitably. However, a conducive environment for agricultural policy is required in developing countries in Asia, sub-Saharan Africa and South America. International agricultural research and development agencies must train and create the next generation of crop improvement scientists, help developing countries create modern agriculture infrastructure, and empower farming communities by establishing and implementing farmer-centric agricultural policies. Modern technologies combined with farmer-friendly agricultural policies will transform agriculture and ensure food and nutrition security. ❐

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Published online: 28 September 2021
https://doi.org/10.1038/s41587-021-01079-z

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Acknowledgements

The authors thank the Deputy Vice-Chancellor Research, The University of Western Australia, and Director General, ICRISAT for supporting an international workshop in Perth, Australia, to brainstorm topics in the article. R.K.V. acknowledges support from the Bill & Melinda Gates Foundation for undertaking research on seed delivery systems through the Tropical Legumes projects at ICRISAT.

Competing interests

The authors declare no competing interests.