POLICY FORUM

AGRICULTURE

Can the global drone revolution make agriculture more sustainable?

Rapid growth in drone use is upending expectations but also inducing trade-offs

Ben Belton[1,2], Leo Baldiga[3], Scott Justice[4], Bart Minten[5], Sudha Narayanan[6], Thomas Reardon[2,7]

Use of drones has increased considerably over the past decade, reshaping activities as diverse as warfare, entertainment, delivery services, and disease control. One of the most consequential uses of drones—in agriculture—has taken off globally within only the past 5 years. This is upending expectations and may help to reconcile a fundamental sustainability dilemma—how to produce more food by using fewer inputs—but is also inducing trade-offs. This rapid change has been largely unnoticed by researchers outside of the specialized technical worlds of aeronautical engineering and precision agriculture. Little academic attention has been paid to the use of agricultural drones beyond the laboratory or trial plot. Evidence of the extent and effects of drones' real-world use is partial and fragmentary. We explored evidence and hypotheses about global agricultural drone diffusion and its implications for sustainability and set out an agenda for future policy and science.

Drones perform a growing array of tasks on farms, including sowing seeds; spreading fertilizers and feeds; spraying herbicides, pesticides, and fungicides; counting livestock; monitoring and mapping fields; and assessing crop health and yields. Crop

PHOTO: SIMA TIANMIN/VCG/GETTY IMAGES

A worker uses a drone to spray pesticide in a paddy field in Ji'an, Jiangxi Province, China, June 2020.

spraying is the most common agricultural drone use worldwide, followed by spreading fertilizers and broadcasting rice seed and cover crops. This multifunctionality makes drones powerful tools, with applications in virtually all types of farming. Crucially, drones may also improve crop yields and enhance sustainability compared with conventional practices.

The rapid rise of drones is helping equalize global inequalities in access to agricultural technology, putting in the hands of farmers in the Global South equipment as sophisticated as that previously only available to large farmers in the Global North. For example, smallholder rice farmers in Asia can now access, for as little as $10 per hectare from an outsource service provider, technology with capabilities comparable with the most state-of-the-art computer-assisted $400,000 ground rig on a 1000-ha soybean farm in the American Midwest. This pattern of technological leapfrogging is reminiscent of the shift from cash to mobile payments in many Global South countries.

INNOVATION AND GLOBAL DIFFUSION

Remote-controlled aircraft have been used in agriculture since the 1980s in some countries. But only in the past decade has a confluence of innovations linked to the design and manufacturing of multirotor drones made these machines easier to operate, more versatile, and increasingly useful to farmers, leading to a sudden global boom. The earliest multirotor drones used in agriculture were very small and could perform few tasks, but improvements in drone design have given rise to larger models capable of carrying heavier loads. Recent models are designed to carry loads of up to 100 kg—more than the weight of a typical sack of fertilizer. This capability has made drones suitable for a wide variety of agricultural tasks and for use on farms of all sizes.

Drone batteries have become smaller, lighter, longer lasting, and much faster charging, reducing downtime between flights to the brief period required to refill inputs and swap over a battery. Use of drones on farms was initially limited to "crop scouting" with cameras, and later to crop spraying by using motorized pumps. Recently, these functions have expanded. Advances in the design of drone attachments such as rotary atomizers (for spraying liquid crop protectants) and granule spreaders (for broadcasting seeds, fertilizer, and feed) make it possible to adjust droplet sizes and flow rates, substantially increasing the efficiency and evenness of input application. These attachments have been modularized, making it easy for a single drone to perform multiple tasks.

Early farm drones required a lot of skill to fly. Since then, miniaturization of improved sensors and software upgrades have greatly simplified flight planning and navigation and increased flying accuracy and automation, making drones easy to pilot.

The first farm drones were expensive for small farmers. Although this is still true for drone ownership, prices have fallen dramatically because of rapid technological advances and competition (*1*). Moreover, service provision by small businesses, farmer groups, and cooperatives—all of which hire out drones with pilots—has made it easy for farmers to access drones at rates similar to or lower than those paid to agricultural laborers (*2*).

All of these improvements have contributed to rapid global drone diffusion, the geography of which has been surprising. The agricultural mechanization revolution—using tractors and combine harvesters to speed up planting and harvesting and save labor—began in the Global North in the 1890s and took more than a century to reach parts of Asia. By contrast, the agricultural drone revolution began in China less than a decade ago and has spread rapidly from there to both the Global North and Global South. Two Chinese companies, DJI and XAG, produce the vast majority of drones used in agriculture worldwide.

To give a sense of the scale and extent of recent diffusion, the figure depicts reported numbers of agricultural drones operational in 10 countries in 2024. These countries span East, Southeast, South, and West Asia and North and South America. They are major agricultural economies that together account for 62% of the world's farms, 46% of its rural population, and 39% of its cropland (*3*). The figure also depicts the intensity of agricultural drone diffusion (drones per area of cropland) in relation to a measure of relative economic development for each country (purchasing power parity gross domestic product per capita). Agricultural drones are present in many other countries and regions, but we were unable to obtain estimates of numbers in those locations.

These data suggest four broad patterns of agricultural drone diffusion by country. We outline these below, in order of the intensity of that diffusion. To explain differences in diffusion across space, we characterized countries with respect to their relative abundance of land and labor, income level, prior adoption of agricultural mechanization before drones, and drone-related policy environment. We hypothesize that these factors condition the distinctive diffusion pathways seen in each group.

Japan and South Korea

Drone diffusion intensity is greater in these countries than anywhere else. This reflects land scarcity (small farms) to which early drone models were well adapted; labor scarcity and elderly farming populations, creating high demand for labor-saving technology; high income levels, making drones relatively affordable; high prior adoption of sophisticated small-scale agricultural machinery such as rice transplanters; and technology-positive regulatory and policy environments, including government subsidies for drone purchases.

China, Thailand, Turkey, and Vietnam

Drone diffusion has proceeded extremely rapidly in these countries but is yet to reach the intensity of Japan and South Korea. Countries in this group are also land scarce, with many small farms; face rural labor scarcity owing to urbanization and industrialization; are upper-middle income; and have already undergone widespread prior adoption of small-scale agricultural machinery, but with intermediate levels of technological sophistication. Policy approaches to agricultural drones in these countries have ranged from vigorous promotion through large-scale subsidies (China) to proactive modification of prior regulatory frameworks (Thailand). Turkey is somewhat less permissive in this regard; drone pilots must seek permission from police before flying because of security concerns.

Argentina, Brazil, and the United States

Agricultural drone diffusion began more recently in these countries and is proceeding rapidly but at a lower intensity than in Asian first-movers. These countries are land abundant (dominated by large farms), requiring large models of drone that have only recently been introduced. Countries in this group are also labor scarce, upper-middle or high income, and have high prior levels of adoption of sophisticated medium- to large-scale agricultural machinery, particularly on large grain farms. Many farms in these countries already own or use the services of expensive self-propelled or tractor-mounted spraying rigs or crop-dusting aircraft. As a result, drones were initially confined mainly to servicing areas where conventional machines have difficulty operating (such as hilly or boggy terrain, or close to pylons), but the range of uses is diversifying rapidly to include a wide variety of specialty crops. These countries have only very recently begun to update regulatory frameworks to accommodate and encourage agricultural drone use. Agricultural drone use in the United States is more highly regulated than in other countries in the group, and recent legislation has banned the import of some DJI drones, potentially slowing future diffusion there.

India

The total number of agricultural drones in India is quite large, but the intensity of diffusion is low. India is land scarce (dominated by small farms), labor abundant in some areas but scarce in others, a lower-middle-income country, and has moderate prior levels of basic small- to medium-scale agricultural mechanization. Government policy here is a two-edged sword that actively promotes drones in agriculture by providing hardware and training to rural women's groups but bans drone imports because of security concerns and with the aim of fostering an infant industry. Moreover, agricultural drone pilots must seek permission before flying. Combined with an abundant low-wage rural workforce and the semi-subsistence orientation of cereal production in many parts of the country, these factors mean the intensity of drone diffusion to date has been low.

Similarly, farm drone use has yet to emerge in most of sub-Saharan Africa in part because of farm labor not yet becoming scarce, as reflected in the limited diffusion of even basic conventional farm mechanization (*4*). Legal restrictions may prevent agricultural drone services emerging at all in some North African countries such as Egypt, where they are very tightly regulated because of security concerns. Restrictions in some countries involved in conflicts, including Myanmar, have ended the emergence of nascent agricultural drone sectors. Strict regulatory environments have slowed the takeoff of agricultural drones in labor-scarce, high-income locations, including Canada and the European Union, as well as in some middle-income countries such as South Africa and the Philippines.

IMPLICATIONS FOR SUSTAINABILITY

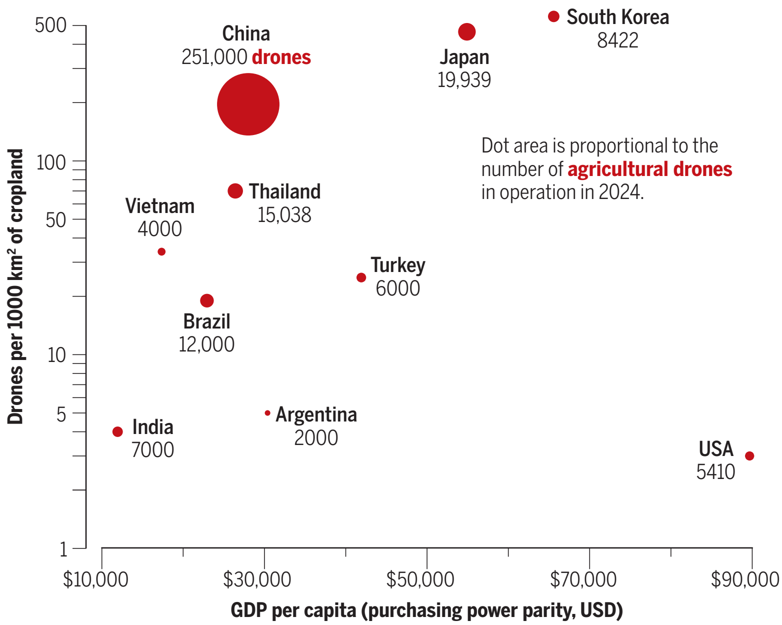
Drones may affect agricultural sustainability through three main channels: productivity and resource use efficiency, rural livelihoods, and human health. These variables may reinforce one another, bringing about benefits to society and the environment. But there can be trade-offs that bring new negative externalities, especially in the context of the Global South.

Productivity and resource use efficiency

In theory, drones can be used to implement sustainability-enhancing "precision agriculture," by using sensors to capture spec-

Intensity of drone diffusion

Drone diffusion (drones per unit of cropland) and number of operational agricultural drones in 2024 are shown for 10 countries, in relation to purchasing power parity gross domestic product (GDP) per capita (*3*). The numbers under each country are the number of agricultural drones operational in 2024. See supplementary materials for details on data.



tral information from plants, analyzing it to provide crop health assessments, and using that analysis to support highly targeted variable-rate application of fertilizers or pesticides (*5*). In practice, such techniques have yet to be widely adopted (*2*), in part because different types of drones are currently required for multispectral sensing and input application. Nevertheless, drones may already contribute to environmental sustainability in several ways.

Drone attachments—rotary spreaders and atomizers—distribute seeds and fertilizer more evenly and disperse pesticides more effectively than broadcasting by hand or with "backpack sprayers" (a common practice on small farms in the Global South). Emerging evidence suggests that drones may reduce seed, fertilizer, and pesticide use by 20% or more compared with manual techniques [for example, (*6*)]. The even placement of seeds and fertilizer and improved penetration and deposition of fine spray droplets inside the crop canopy achieved with drones may increase utilization of these inputs by plants, reducing environmental losses and enhancing resource use efficiency (*7*).

Drones may raise crop yields by eliminating plant damage and soil compaction caused by heavy tractors (*8*). Using battery-powered drones to distribute inputs may reduce energy consumption compared with using conventional heavy machinery (*9*). Drones can also make it easier to implement conservation agriculture practices that reduce soil CO_2 emissions, such as relay sowing and seeding cover crops, because seed can be sown over mature crops in the field from the air. Drones might also allow smaller field sizes to be managed efficiently, reducing farm consolidation and enhancing landscape-level biodiversity (*10*).

Although data-intensive drone operations and analytics that would enable precision agriculture and variable-rate input applications (such as spot-spraying and targeted fertilizer spreading) are not yet widely used by farmers (*2*), these functions will likely become more deeply integrated into everyday practice over time as artificial intelligence and data-processing capabilities advance and as new generations of drone are developed that incorporate both sensing and input application functions. These functions have great potential to drive further improvements in input use efficiency and crop yields, but with the trade-off that the computationally demanding operations required to power them would sharply increase drones' energy demands.

A further promising area in which drones may reduce crop losses and bolster food security is through integration into early-warning systems for disaster risk reduction. For example, remotely sensed satellite data on soil moisture and vegetation cover can be used to predict possible locations for emergent locust infestations, and drones can be directed to these areas to detect locust concentrations and spray to prevent swarms developing (*11*).

Rural livelihoods

Drones may raise farm incomes and affect rural employment through several channels, contributing to the sustainability of rural livelihoods. Drones save labor by dramatically reducing the amount of time needed to apply crop inputs [for example, (*12*)]. This may free rural households to work off-farm, increasing and stabilizing incomes and managing risks, or to use labor for diversifying on-farm into high-value crops such as vegetables. By reducing the quantity of inputs and labor applied to each hectare of land, drones can save farmers money [for example, (*2*, *7*, *13*)].

In combination with conventional agricultural mechanization, agricultural drones eliminate most of the remaining physically demanding work associated with farming. In doing so, drones may help aging farmers to persist, as seen in South Korea, where the average farmer's age is over 60 years and drones already service 30% of farmland (*8*). Conversely, by minimizing the drudgery associated with farming, drones may increase agriculture's appeal to younger farmers, reducing the likelihood that they abandon it. Drone outsource service provision is itself an attractive occupation for rural youth. For example, nearly half of China's agricultural drone pilots are aged 30 or below (*14*). The drone revolution thus increases demand for skilled labor in rural areas.

However, the labor-saving nature of drones can induce a trade-off. In the Global North, agricultural drones are unlikely to displace much labor because displacement already occurred during earlier waves of conventional farm mechanization. But in the Global South, drones will displace some of the poorest agricultural laborers currently hired to spray, fertilize, or weed crops. However, farmers are most strongly incentivized to adopt drones in places where agricultural labor is scarce and rural wages are high, so relatively little displacement is likely to occur in low-income, labor-surplus countries. Moreover, the gender implications of drone adoption are poorly understood. For example, it is not clear whose labor is released or displaced, whether women can access opportunities to provide drone services, or whether drone services affect women's agency over farm management decisions.

Human health

A major benefit of spraying crops remotely by use of drones is that it substantially reduces the risk of farm workers' direct exposure to toxic chemicals, compared with applying them with handheld sprayers. The informal nature of farm work in the Global South means that safety precautions are often not followed when spraying by hand, so occupational health benefits there will be particularly large. However, drones typically fly two or more meters off the ground. This may increase the risk of spray drift to neighboring farms or bystanders, relative to ground-based spraying (*15*), particularly where regulations are absent or weakly enforced or where small farms produce a mixture of crops that could easily be damaged by stray herbicides.

IMPLICATIONS FOR SCIENCE AND POLICY

Like all important new technologies, drones arouse uncertainty and create new dilemmas. Several issues at the nexus of science and policy should be prioritized to help enhance the potential benefits and address the dilemmas.

Facilitating inclusive agricultural drone diffusion

Drone diffusion is occurring rapidly in countries with favorable conditions, but inequalities are emerging in these countries between the most productive agricultural zones and more peripheral areas. A new "digital divide" is also emerging at the global scale as drones diffuse more rapidly in some areas than others. Countries where favorable economic conditions for drone takeoff exist but diffusion is hindered by restrictive policies (for example, South Africa and the Philippines) can draw from the experience of high-diffusion countries to adjust the policy mix in ways that accelerate diffusion safely and responsibly. Drawing on these experiences can also help avoid wasteful investments in ineffective promotional programs.

The basket of policy tools that could accelerate diffusion includes subsidies and finance for drone purchases and the establishment of training, accreditation, licensing, and insurance schemes for drone operators. Depending on intent, these efforts can be designed to cater to individuals, small businesses, farmer groups, or franchises. Restrictive policies such as requiring drone pilots to seek permission before flying can be avoided by introducing standards that ensure pilots are proficient. Remote identification systems can allow drones to be tracked in real time and excluded from entry into sensitive areas by geofencing. Categorizing agricultural drones as farm machinery so that they do not fall under the purview of aviation regulations can greatly simplify their governance.

Reducing input use and raising farm yields

Current use of agricultural drones may already be inducing sustainability gains through lower input use and higher crop yields. But these gains have yet to be studied systematically, and few if any standard operating procedures specifically designed to maximize beneficial outcomes exist. Research in this area could lead to changes in labeling for agrochemicals that reflect higher efficacies when applied by drone, mandating lower levels of use as compared with that for conventional applications. Unlocking the power of drones to implement more sophisticated forms of precision agriculture may require public and private investments in digital infrastructure. For example, 5G networks enable reliable high-volume data transfer and real-time kinematic positioning networks to allow for more accurate spatial positioning of drones. Promoting precision agriculture will also require deeper integration of drone sensing, analytical, and input application functions, with training and extension needed to enable farmers, particularly smallholders, to adopt. Investments in public goods such as regional early-warning systems for locust monitoring and control can minimize crop losses and raise agricultural productivity.

Avoiding rural labor displacement

Policies to address potential displacement of farm workers by drones could include training for reskilling (including as drone operators or pilots' assistants). Cash buyouts and financial support for crop sprayers to acquire drones could reduce loss of income and accelerate the transition.

Minimizing risks to human and environmental health

The shift in many Global South countries from applying inputs by hand to applying them by drone presents a critical opportunity to formalize and professionalize crop spraying. This change would promote greater standardization and safety in an otherwise poorly regulated sector. Doing so would help to mitigate direct risks to human health for sprayers and risks to environmental health posed by excessive agrochemical use and spray drift. Regulatory frameworks can be designed to ensure that drone service providers must undergo training on safe agrochemical use. Such regulations should be designed in ways that do not exclude smaller players, who may need time and support to receive accreditation.

Maintaining technological sovereignty

The global drone market is highly concentrated. As drones become ubiquitous on farms worldwide, there is a possibility that future world events could disrupt supply or make drones vulnerable to cyberattacks (*10*). Public and private investments in research and development can support new drone technologies that induce competition and counter market concentration, but success is not guaranteed. Countries prioritizing national security concerns run the risk of denying farmers access to the most advanced and cost-effective drone technologies.

Ensuring equitable data use

Concentration in the global drone market raises questions about data sovereignty. These concerns will deepen as more data-intensive uses of agricultural drones grow. Who owns and has access to these data, where they are stored, and how they are used have implications for farmers' privacy, the ability to generate public goods, and—possibly—national security. Widespread information-intensive uses of drones would generate vast amounts of crop-specific geospatial data. If aggregated for processing with predictive models, these data could provide public goods, including seasonal yield predictions, accurate crop production estimates, or early warnings of pest infestations. Information collected by drones may also be used for verification of crop damage to support insurance payouts or compensation.

Conversely, if data are treated as the exclusive intellectual property of drone companies, they may become commodified, such as by selling user information for advertising. Such developments might give rise to business models in which drone companies have more to gain by monetizing farmer data than by providing high-quality services. Policy-makers may wish to consider legislation and public-private partnerships that ensure that drone data are retained on servers in the countries where they are generated and facilitate their use for development of public goods, without undermining farmer privacy.

The drone revolution is upending historical patterns of agricultural technology diffusion. In just 5 years, millions of farmers across Asia and beyond, many of them smallholders, have gained access to a powerful new technology with a broad and rapidly growing array of practical uses. There are strong indications that drones can raise the efficiency and productivity of farming, improve worker safety, and enhance rural livelihoods, but these impacts have yet to be evaluated rigorously. Applied interdisciplinary research and corresponding policy responses are urgently needed to steer the global drone revolution in ways that make agriculture more sustainable. □

REFERENCES AND NOTES

1. X. T. Zheng, *Yicai News* 12 June 2024 [in Mandarin]; https://www.yicai.com/news/102390075.html.
2. X. Quan, Z. Wang, T. Daum, X. He, R. Doluschitz, *agricultural engineering.eu*, **79**, 180 (2024).
3. International Food Policy Research Institute (IFPRI), Global agricultural drone distribution. Harvard Dataverse (2025); https://doi.org/10.7910/DVN/BWUQXJ.
4. X. Diao, H. Takeshima, X. Zhang, Eds., *An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia?* (IFPRI, 2020); https://doi.org/10.2499/9780896293809.
5. G. Sylvester, *E-Agriculture in Action: Drones in Agriculture* [Food and Agriculture Organization of the United Nations (FAO), International Telecommunication Organization, 2018].
6. L. Wang *et al.*, *Agriculture* **12**, 397 (2022).
7. S. Meesaragandla, M. P. Jagtap, N. Khatri, H. Madan, A. A. Vadduri, *Results Eng.* **21**, 101870 (2024).
8. E. Ozkan, "Drones for spraying pesticides" (Ohio State University Agronomic Extension, 2023); https://agcrops.osu.edu/newsletter/corn-newsletter/2023-05/drones-spraying-pesticides.
9. Y. Seo, S. Umeda, N. Yoshikawa, *Int. J. Agric. Sustain.* **21**, 2247803 (2023).
10. H. H. Zeddies, G. Busch, M. Qaim, *Sci. Rep.* **14**, 15607 (2024).
11. G. A. Matthews, *Agronomy* **11**, 1052 (2021).
12. X. Quan, Q. Guo, J. Ma, R. Doluschitz, *Precis. Agric.* **24**, 1965 (2023).
13. FAO, ICRISAT, "Digital agriculture in action: Selected case studies from India," FAO Investment Centre, Country Investment Highlights no. 17 (FAO, 2022); https://doi.org/10.4060/cc0017en.
14. Z. Huang, H. Chen, 2024. "Regulatory framework for drone operations for agriculture in China: Challenges and opportunities," presentation for FAO webinar, "Drones for agriculture: Opportunities and challenges for the establishment of regulatory frameworks," 20 March 2024; https://www.youtube.com/watch?v=LP6w45taHI8&t=1s.
15. Organisation for Economic Co-operation and Development (OECD), "Report on the state of the knowledge: Literature review on unmanned aerial spray systems in agriculture," OECD Series on Pesticides, no. 105 (OECD Publishing, 2021).

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SUPPLEMENTARY MATERIALS

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[1]International Food Policy Research Institute (IFPRI), Dhaka, Bangladesh. [2]Department of Agricultural, Food and Resource Economics, Michigan State University, East Lansing, MI, USA. [3]Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI, USA. [4]Independent Consultant, Yangon, Myanmar. [5]IFPRI, Vientiane, Laos. [6]IFPRI, New Delhi, India. [7]IFPRI, Washington, DC, USA. Email: ben.belton@cgiar.org