Advancing Agricultural Economics Research Using Trajectory Data: Evidence from Drones

Zhang Yang, Zhang Hangyu, Liu Xinyu* and Hu Shiyun

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1 Context

The sustainability of global agriculture is fundamentally challenged by a nexus of interconnected crises comprising labor scarcity, environmental degradation, and food security. However, the existing market mechanisms and public policies aimed at addressing these challenges have long been constrained by a fundamental "measurement gap". On the one hand, as a cornerstone of traditional agricultural economics, farm survey data is of fundamental importance. Yet, this data collection method suffers from several systematic flaws, including recall bias, errors in measuring key variables (such as land area), and infrequent sampling (usually annual). For example, research have found that smallholders often report plot sizes that are up to five times larger than the actual size. Such low-quality data not only distorts our understanding of farm productivity and behavior but also undermines the efficacy of policy interventions. On the other hand, although satellite remote sensing technology has achieved significant success at the macro level (e.g., deforestation monitoring, urban expansion), it has a "behavioral blind spot" when applied to micro-level agricultural production. Satellite data can capture the "status" of farmlands at high frequency, such as crop greenness (NDVI) or harvest outcomes, but it is almost impossible to observe the high-frequency "behaviors" that generate these outcomes, such as the true operational quality of agricultural machinery services, the real-time application of chemicals (fertilizers, pesticides), or labor inputs in the field. It is precisely these micro-level behaviors that lie at the core of market failures (e.g., information asymmetry) and policy failures (e.g., lack of compliance). With technological advancements in drone systems nowadays, the trajectory data it generated are emerging as essential tools for bridging the gap and transform the traditional agriculture (See Figure 1).

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*Corresponding author, E-mail: xyliu2018@nsd.pku.edu.cn

[Figure 1 about here]

2 Purpose

The main purpose of this study is to propose and validate a replicable novel analytical framework leveraging operational trajectory data from agricultural UAVs to systematically address the aforementioned “behavioral blind spot”. We define this process as an “Engineering-to-Economics Translator”. Specifically, this process “translates” raw data generated by drone operations into structured variables for economic analysis. It converts parameters originally used for engineering control, including second-level flight paths, instantaneous spray/dispense flow rates, flight speed, and altitude, into variables with clear economic analytical meaning. Through this methodological innovation, this study aims to generate scalable, high-resolution quantitative indicators for three key economic issues that have traditionally been difficult to measure: (1) service quality and moral hazard in agricultural outsourcing; (2) actual application of inputs and spatial distribution of chemicals (fertilizers, pesticides); (3) Jevons Paradox arising from the adoption of emerging technologies (*e.g., UAV lifting may facilitate the over-exploitation of previously untouched forests*). This study leverages trajectory data with high temporal resolution and precision to offer novel insights into micro-level agricultural decision-making, policy evaluation and sustainable development.

3 Methods

This study utilizes a large-scale, high-precision panel dataset sourced from Nanping City, Fujian Province, China. The dataset is derived from the operational data of mainstream UAV platforms (*e.g., DJI Agriculture*), spanning the period from 2020 to 2025. The dataset covers an operational area of 1.3756 million acres (about 91,333 hectares) across Fujian’s main agricultural zones, encompassing diverse terrains such as hills, mountains, and plains, as well as various crop types including tea, bamboo, and rice (See Figure 2 that visualize UAV trajectories across diverse scenarios). The unique advantage of this data lies in its exceptional spatiotemporal resolution, featuring meter-level spatial precision and second-level temporal frequency. Our data analysis process mainly includes three steps: (1) *Data processing*: This step involves two aspects. *On one hand*, it is data extraction and matching, where raw drone trajectory data (including GPS coordinates, speed, flow rate, and timestamps) are spatially aligned with their corresponding field boundaries in a GIS environment; *on the other hand*, it is temporal aggregation, where second-level trajectory points are consolidated into clearly defined ”field operation” events. (2) *Economic variable feature engineering*: The core of this ”transformation” lies in the ability to objectively calculate key economic variables, and the shape of the trajectory can serve as a quality indicator, such as fertilizer amount (kg/ha). *For instance*, for a specific field, this can be achieved by integrating the instantaneous flow rate (kg/s) over the operation time and field width, eliminating the need to rely on the farmer's subjective self-reporting. This analysis process enables in-depth empirical research on three representative drone scenarios: pesticide spraying, precision fertilization, and aerial logistics in mountainous areas. (3) *Causal Effect Evaluation*: Unlike traditional agricultural monitoring data, the high-frequency nature of drone trajectory data (second-level sampling) enables the derivation of massive high-dimensional covariates such as terrain curvature and flight path geometry. However, this also introduces challenges in identifying selection bias and omitted variables. The Dual Machine Learning (DML) framework employs a two-stage estimation process (*Stage 1*: fitting residuals between treatment and outcome variables using ensemble learning; *Stage 2*: bias-corrected regression). This approach flexibly controls for spatio-temporal heterogeneity and nonlinear interactions without assuming functional forms, enabling consistent estimation of the causal effects of technical parameters on outputs or the environment. It also facilitates heterogeneous analysis of policy impacts.

[Figure 2 about here]

4 Findings

This study's empirical analysis generated key findings from these three scenarios:

First, in pesticide spraying services, we empirically tested the prevalent *principal-agent* problem (moral hazard) in agricultural outsourcing using service quality. By combining trajectory coverage density (to identify whether the drone operator skips parts of the area to save time) with water usage per unit area (as a proxy for pesticide dilution), we constructed an objective service quality index(See Figure 3). Analysis found that, in the absence of effective supervision, the operator's work quality (*e.g.*, excessive flight speed, insufficient spraying density) significantly deviated from the optimal standard stipulated in the contract, directly leading to a decline in service quality. This finding demonstrates the tremendous potential of trajectory data in designing and executing *pay-for-performance* agricultural service contracts.

[Figure 3 about here]

Second, in the fertilization process, trajectory data provided objective *ground truth* for evaluating environmental policies such as *fertilizer reduction*. By integrating instantaneous flow data, we obtained real fertilizer application rates at the plot level. When comparing this objective measurement with traditional self-reported data from farmers, we discovered systematic biases. Evidence from trajectory data shows that the true situation of policy compliance is far more complex than self-reported data indicates. This methodology provides governments with a near-real-time policy monitoring tool, effectively correcting traditional self-reporting biases for more precise policy evaluation and intervention.

Third, in mountain lifting operations, the study revealed the dual effects of technology adoption. On one hand, cost-benefit analysis quantified the significant substitution effect of UAVs on traditional production factors: in Fujian's mountainous regions, UAV lifting effectively replaced scarce and expensive labor and avoided the high capital expenditure and ecological damage required for building mountain roads. On the other hand, technological progress could also bring unintended negative environmental damage. By overlaying lifting trajectories with geographical data from forest conservation areas, we examined whether this technology induced *illegal logging* (rebound effect). Preliminary evidence suggests that the UAV's significant reduction in timber transport costs made previously unprofitable marginal forest areas economically viable for logging, potentially increasing the risk of deforestation in certain regions.

5 Significance

The significance of this study lies in its systematic demonstration of how high-precision UAV trajectory data can fundamentally change the way we observe, understand, and govern agricultural production behaviors. It provides a novel and scalable micro-level data paradigm for agricultural economics, development economics, and environmental sciences, whose importance extends beyond a single technological application.

However, to fully unleash the potential of trajectory data, three major challenges must be overcome:

1. *Data standardization and governance:* Currently, data formats are inconsistent and highly concentrated in private platforms, and a unified data governance standard must be established to balance data openness (for public research) with market competition (platform interests).

2. *Data privacy and ethics:* High-precision behavioral data raises serious concerns about farmer data sovereignty and privacy protection.

3. *Technological accessibility and fairness:* It is crucial to prevent the expansion of the "digital divide" and ensure that smallholders and resource-poor operators can equally benefit from technological advancements and data value.

In conclusion, to fully realize the value of high-frequency trajectory data and promote the transformation of agriculture into a more efficient, equitable, and resilient paradigm,

it is necessary to integrate *technological innovation* (such as our data process), *adaptive regulation* (establishing data governance rules), and *inclusive development* (enhancing smallholder access capabilities). This integrated strategy is a vital pathway toward sustainable modern agricultural development in the future.

Keywords: UAV Trajectory Data; Agricultural Economics; Principal-Agent Problem; Policy Evaluation; Sustainable Development

Appendix: Figures

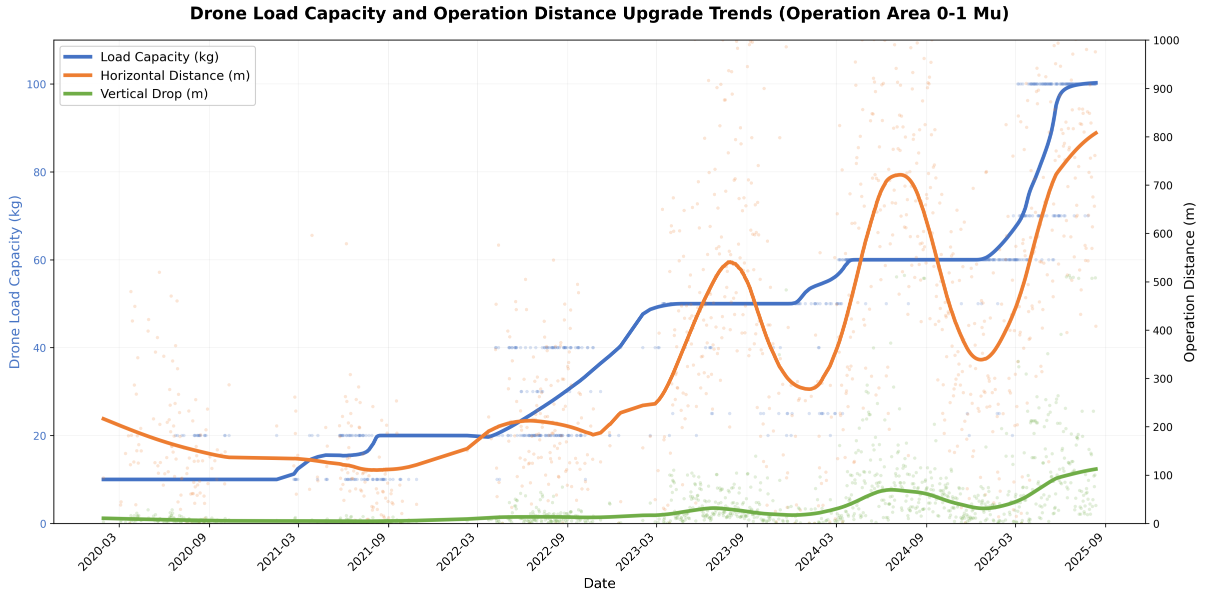
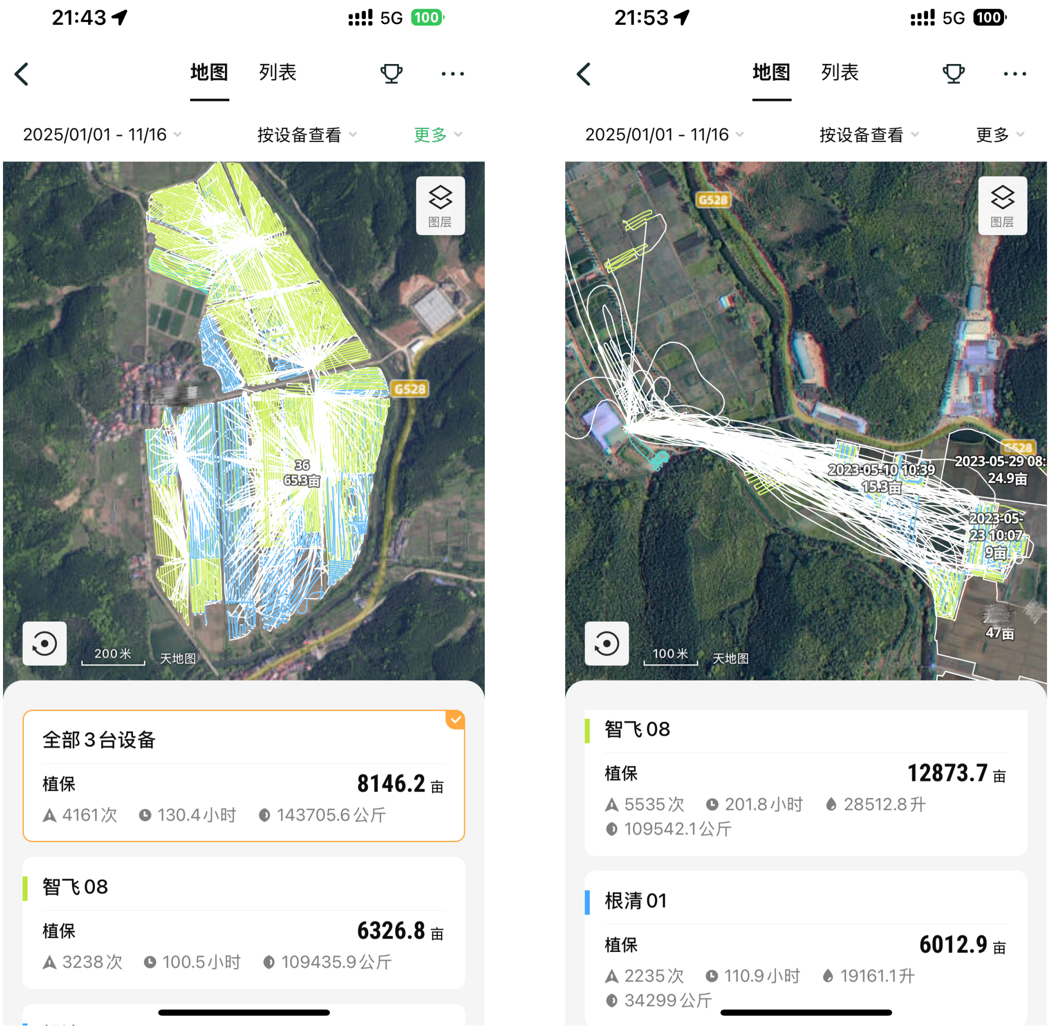


Figure 1: Drone Upgrade Trends

This chart illustrates the rapid technological advancement of agricultural drones from 2020 to 2025. Load capacity increased tenfold, from 10 kg to 100 kg, while horizontal operating range expanded from 150-200 meters to 700-800 meters, and vertical drop capability rose to 100-120 meters. These coordinated improvements have transformed drones from simple crop sprayers into robust mountain logistics platforms. Now, they can transport heavy payloads (e.g., 80 kg of bamboo) across difficult terrain, covering horizontal distances of 500 meters and elevation changes of 200-300 meters, thereby enabling crucial applications in previously inaccessible mountainous agricultural areas.



全部3台设备
植保 8146.2亩
4161次 130.4小时 143705.6公斤

智飞08
植保 6326.8亩
3238次 100.5小时 109435.9公斤

智飞08
植保 12873.7亩
5535次 201.8小时 28512.8升
109542.1公斤

根清01
植保 6012.9亩
2235次 110.9小时 19161.1升
34299公斤

(a) Plant protection

(b) Hoisting

Figure 2: Screenshot of the interface of the unmanned aerial vehicle (UAV) operating system
Notes: Data is collected from DJI Agriculture Services, a drone pilot. The screenshot was authorized by the interviewee.

The image on the left side shows the spatial distribution of the operation trajectories of three drones under a certain pilot from January 1 to November 16, 2025. In the image, green and blue lines represent the flight paths of different devices, densely intertwined in the core operation area, demonstrating highly concentrated and continuous operational characteristics. Most flight routes are in regular parallel lines and have clearly defined plot boundaries, indicating that autopilot technology was widely used during operations to achieve efficient and precise pesticide spraying. Data show that the three devices cumulatively covered 8,146.2 mu of area, completed 4,161 flights, had a total operation time of 130.4 hours, and applied 143,705.6 kilograms of pesticides, reflecting high operational intensity and outstanding efficiency. The image on the right side shows the flight trajectories of the 'Zhifei 08' and 'Genqing 01' drones used by a certain pilot during the same period. In addition to the regular farmland operation routes, it also includes several non-operational trajectories connecting mountainous plots, reflecting the mature application of drones in providing lifting services in mountainous areas (such as transporting bamboo, bayberries, bamboo shoots, etc.).

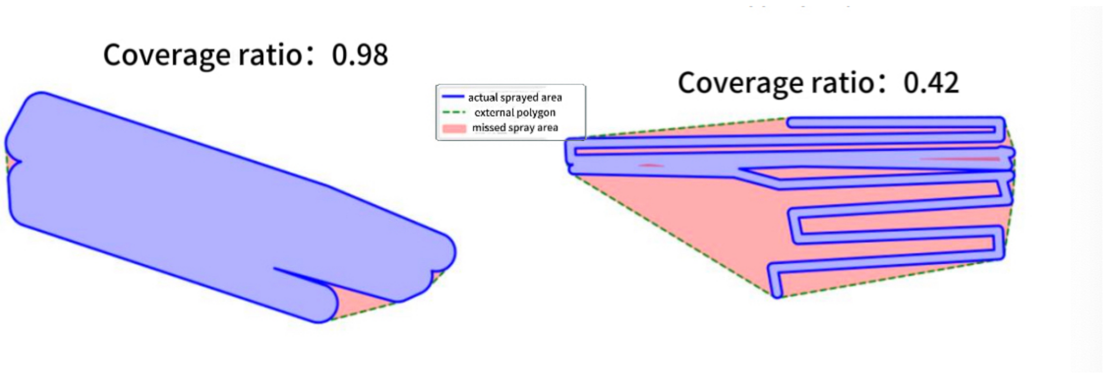


Figure 3: Trajectory quality measured by coverage ratio

This figure demonstrates trajectory quality using coverage ratio. It is calculated by the area of the buffered flight path divided by the area of the convex hull (the smallest convex polygon containing all trajectory points. This figure offers us two insights. First, in terms of effectiveness, drones have an effective spray width, and if the row spacing exceeds this effective spray width, deposition quality decreases. According to DJI (2024) operational specifications, even the T60, the heaviest-lifting aircraft in 2024, has a maximum recommended spray width of only 7 meters for rice operations. From actual data, even in relatively standardized autonomous flight trajectories (left figure), about 10% of cases still exceed a 7-meter row spacing, indicating potential quality risks in missed spray areas. Second, in terms of comparability, manually flown trajectories are less regular in shape (right figure), making row spacing difficult to define precisely. Therefore, ”the ratio of the trajectory buffer area to the minimum convex polygon” allows the quality of manual mode trajectories to be comparable with those of autonomous mode.