



Comparison of spray drift between spraying drone and conventional airblast sprayer in vineyards

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ABSTRACT

Spraying Unmanned Aerial Vehicles (UAVs) are autonomous airborne platforms that primarily operate on pre-determined flight plans and spraying missions. Although spraying UAVs are increasingly used for plant protection in vineyards, limited experimental evidence exists on how operational parameters influence spray drift under real field conditions, especially in European vineyards. This study quantified ground-level drift from a UAV sprayer in a commercial vineyard, evaluating two flight altitudes (2.0 m and 2.5 m AGL), two flight speeds (1.0 and 1.5 m/s), and three application strategies (inter-row with and without a buffer line, and over-row with a buffer line). An additional set of replicates using a conventional air-assisted sprayer was included as a reference for current vineyard practice. Spray drift was measured at multiple downwind distances using filter paper collectors and analysed with laboratory spectrophotometric methods following ISO 22,866. Drift from UAV applications was highly concentrated near the field boundary and declined sharply within the first 5 m for all configurations. Flight altitude was the dominant driver: increasing AGL from 2.0 m to 2.5 m raised drift at the closest sampling point by 30–70 %. Higher flight speed (1.5 m/s) increased drift by 10–20 % compared with 1.0 m/s. Applying a buffer reduced drift by up to 60 %, particularly in inter-row spraying. Under optimal UAV settings (2.0 m AGL, 1.0 m/s, buffer applied), drift became negligible beyond 10 m downwind. Compared with the conventional air-assisted sprayer, UAV applications under optimised conditions reduced drift at the closest sampling distance by approximately 65–70 % and showed substantially lower drift beyond 10 m. These findings demonstrate that appropriate UAV operational settings can significantly reduce off-target movement and offer a lower-drift alternative to conventional terrestrial sprayers in vineyard applications and such mitigation strategies should always be considered prior to designing a flight plan or spray mission.

1. Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, are remotely piloted aircraft without an onboard crew. Their use in agriculture has increased rapidly in recent years, supporting operations such as crop monitoring, detection of water and nutrient stress, early pest and disease detection, stand assessment and the application of plant protection products (PPPs) [1]. Spraying drones receive particular interest because they can fly at low altitudes, adapt to irregular and steep terrain, perform vertical take-off and landing and apply low-volume and site-specific treatments. These capabilities reduce operator exposure,

improve work safety and limit crop and soil damage, with relatively low operational cost [2].

Spray drift is defined as the fraction of PPPs transported away from the treated area by air currents during application (ISO, 2015). Drift can contaminate non-target crops, sensitive areas and non-target organisms, including humans. Two types of drift are usually identified. Horizontal drift occurs along the spray direction when airflow carries droplets beyond the target canopy. Vertical drift occurs perpendicular to the spray direction and is mainly influenced by the ambient wind [3].

Drift can be assessed as airborne drift to estimate bystander exposure or as ground deposition to characterise environmental exposure. Drift

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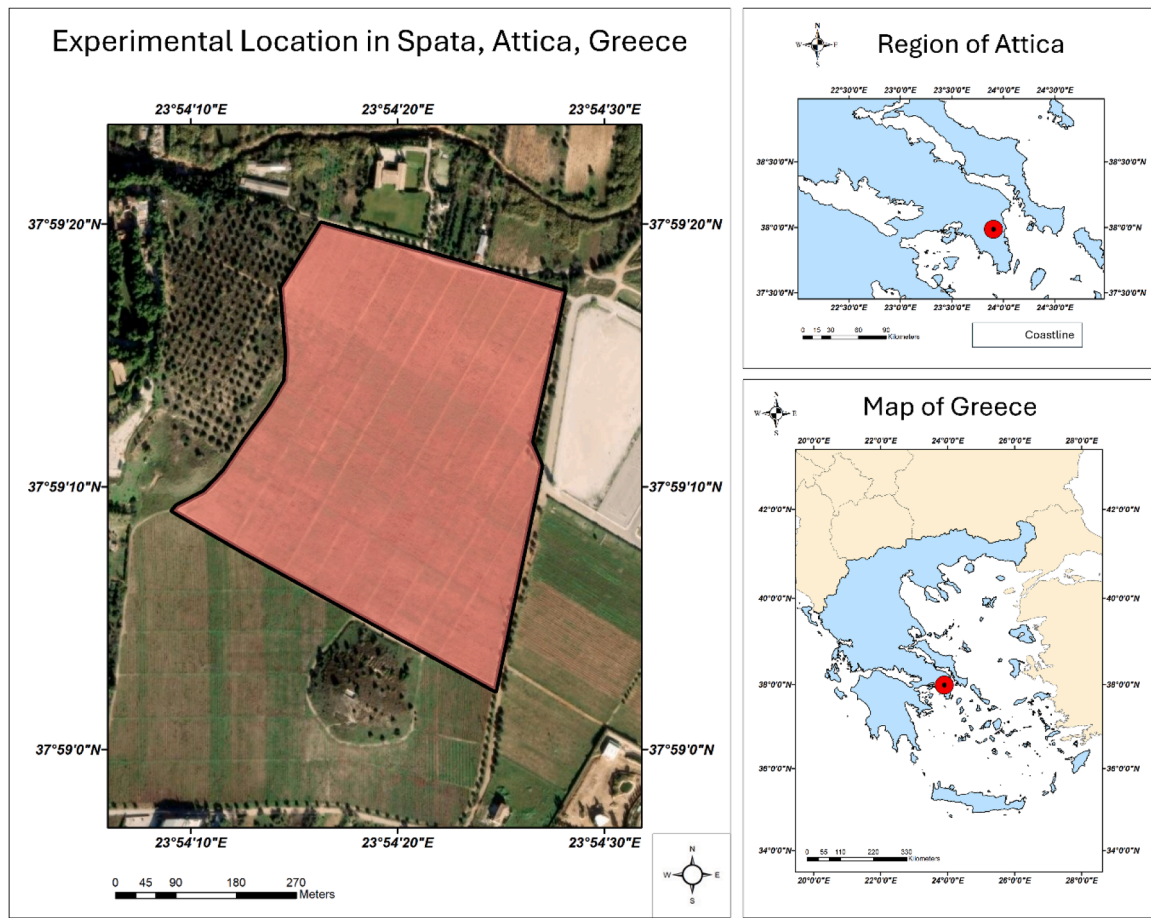


Fig. 1. The location of the experimental site, the experimental vineyard of AUA in Spata, Attica, Greece.

predictions for different application methods and crop types are essential for regulatory risk assessments. For UAVs, it is important to quantify how drift levels and distances compare with ground and manned aerial application, how they align with existing exposure models and whether UAVs introduce specific drift-related risks [4].

Although UAV spraying systems still require optimisation, they hold the potential to offer several advantages over conventional ground-based sprayers in terms of spraying efficiency, if used properly. Despite their relatively high initial investment cost, they can reduce labour requirements, improve application efficiency and ensure access to areas that are difficult or unsafe for tractor-mounted equipment. UAVs also operate with lower energy demand, and using batteries as their primary power source, they can operate on renewable energy sources. Their capacity for targeted applications can enable reduced chemical inputs, lower runoff potential and a diminished risk of groundwater contamination. Operator exposure to plant protection products is also reduced [5], limited to instances when the aircraft returns to the operational base for tank refills, often combined with battery changes to eliminate dead times by traveling multiple times to the operational base. Furthermore, UAVs can function effectively on steep or uneven terrain that may be inaccessible or very dangerous for terrestrial machinery to traverse. They also eliminate soil compaction as they remain airborne throughout the application, and typically require substantially less water for crop protection operations, as most UAV applications use ultra-low-volume spray approaches.

Drift from conventional sprayers such as airblast sprayers is well documented and in some cases may reach up to 50 % of the applied mixture [6,7]. Key technical factors influencing drift include droplet size and the proportion of fine droplets [8]. Smaller droplets remain airborne for longer and are more easily displaced by wind [9]. Meteorological

conditions also play a major role. Drift increases with wind speed [6,10] and high temperature combined with low relative humidity accelerates evaporation, producing more fine droplets and potentially higher secondary (volatile) drift [11].

Several drift-reduction solutions have been tested for conventional sprayers. Grella et al. [12] showed that air-induction nozzles combined with semi-shielded booms can reduce drift by up to 75 % in vineyard weed control and suckering and by up to 92 % in weed-only applications. Fully shielded booms achieved almost complete drift reduction. Vegetated buffer zones further reduced drift by up to 97 %. Vineyard systems are particularly relevant because narrow spacing and steep terrain complicate conventional spraying [13].

Several studies have assessed UAV spraying performance in vineyards, a high value crop that is commonly cultivated in steep terrains. Biglia et al. [14] compared a UAV sprayer with a conventional axial-fan sprayer in full-canopy conditions and found that drone deposition and losses depended strongly on flight mode and nozzle type. Higher UAV cruise speeds such as 3 m per second increased deposition and reduced losses, especially when conventional nozzles were used. Sassu et al. [15] showed that low flight altitude, higher cruise speed such as 2 m per second and correct flight positioning reduced drift. Sarri et al. [16] reported that in steep terraced vineyards UAV spraying required less time than conventional spraying and resulted in reduced off-target losses due to appropriate droplet size.

Drift from UAV spraying in vineyards is generally expected to be lower than drift from airblast sprayers for both coarse and fine droplets. Rotor downwash produces a downward airflow that pushes droplets into the canopy, while airblast sprayers generate an upward trajectory [4, 17]. This can improve inner-canopy penetration. UAV performance, however, depends strongly on flight path in relation to crop geometry.



Fig. 2. (A) The conventional air-assisted sprayer used in the trials, (B) the spraying UAV used in the trials, and (C) an overview of the first 5 m of the sampled area.

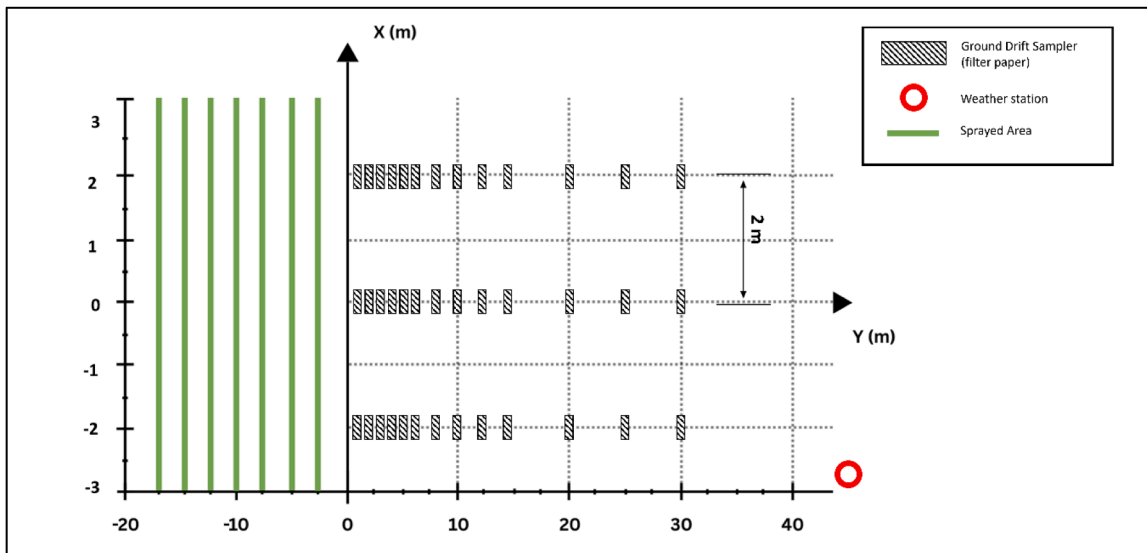


Fig. 3. The experimental design following the ISO 22,866 protocol for ground drift sampling.

Giles and Billing [18] reported different deposition patterns when flying across versus along vine rows. Therefore, UAV operational parameters must be characterised and optimised to ensure uniform deposition and effective pest and disease control.

International adoption of spraying UAVs varies and is directly linked to national regulations across Europe. In Switzerland, drones are used to replace helicopter spraying in steep vineyards, where more than half of the 15,700 hectares are inaccessible to tractors [4]. Application volumes typically range from 80 to 100 litres per hectare. In Germany,

recommended volumes are 40 to 75 litres per hectare. In the United States, most UAV studies focus on high-value crops with low carrier volumes. Giles and Billing [18] applied 47 litres per hectare with a UAV compared to 935 litres per hectare with a conventional sprayer. Across four seasons, ground sprayers used 500 to 1000 litres per hectare, whereas UAV applications used 50 to 100 litres per hectare according to product label recommendations [19].

Herbst et al. [20] evaluated four spraying drones at two flight heights, 1.5 m and 3.5 m, using coarse and fine droplets in two

Table 1

The operational configurations of each trial.

Treatment	Position	Buffer	Altitude (AGL) (m)	Speed (m/s)
A	Over-row	Yes	2.5	1
B	Over-row	Yes	2.5	1.5
C	Over-row	Yes	2	1
D	Over-row	Yes	2	1.5
E	Inter-row	No	2.5	1
F	Inter-row	No	2.5	1.5
G	Inter-row	No	2	1
H	Inter-row	No	2	1.5
I	Inter-row	Yes	2.5	1
J	Inter-row	Yes	2.5	1.5
K	Inter-row	Yes	2	1
L	Inter-row	Yes	2	1.5

Table 2

The wind-related environmental conditions during each trial, averaged across all three (3) replicates.

Treatment	Wind Speed (m/s)	Wind direction (°)
A	1.94	95
B	2.01	93
C	2.03	91
D	2.58	92
E	1.52	95
F	2.40	84
G	1.52	85
H	1.65	97
I	2.22	87
J	1.98	91
K	1.96	97
L	1.77	95
Conventional	2.26	97

conditions: bare ground representing an arable crop and an artificial canopy representing a vineyard. Drift collectors were placed from 3 to 20 m downwind. For the arable condition, drift from coarse droplets matched the standard drift curve and drift from fine droplets exceeded it. For the vineyard condition, coarse droplets produced drift levels below the standard curve and fine droplets produced drift levels similar to it. Average deposition at 20 m downwind was lower than 1 % of the applied mixture across treatments [20,21].

Although interest in UAV spraying has increased, experimental data on how specific UAV operational parameters influence spray drift under real EU vineyard conditions remain limited. Most existing studies compare drones with conventional sprayers or report general deposition patterns, but few quantify how altitude, flight speed and spray buffer zones affect drift generation and downwind transport in vineyards. Inter-row and over-row flight paths, which can substantially alter rotor-canopy airflow, alongside the use of buffer lines, have also not been systematically evaluated and compared against each other.

This study addresses these gaps and aims to increase knowledge on efficient spraying UAV usage and optimal autonomous flight planning, by conducting open-field experiments in a commercial vineyard to: (1) quantify spray drift under different UAV flight altitudes and speeds, (2) compare drift patterns between inter-row and over-row spraying modes, and (3) assess the effect of buffer lines, a widely used drift mitigation strategy in spraying applications, in each UAV spraying scenario and under different operational configurations. By adopting the methodological elements from ISO 22,866, the study provides a detailed characterisation of UAV-induced spray drift and delivers evidence-based guidance for optimising UAV spraying in south-east European vineyard systems.

2. Materials and methods

2.1. Study area

The pilot area of this study was the experimental vineyard of the Agricultural University of Athens located in Spata, Greece (37°59'06" N, 23°54'21" E) (Fig. 1). The vineyard has 2.0 m row spacing with 1.6 m spacing of vines along the row to result in a density of 3125 vines per ha. The average vine height is about 1.5 m, with the leaves and grapes occupying the zone above ground between 0.3 and 1.5 m. The trials of the present study took place between late July and early August 2024. The growth stage corresponding to that period was Veraison (BBCH 81), and the LAI, measured in a total of 12 random sampling locations within the study lines with a LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, USA), averaging at a 1.81 value.

The drone used in these trials was a hexacopter Agras T16 (DJI, Shenzhen, China), equipped with eight (8) XR11001VS nozzles. Flight testing prior to the field trials took place in both the field segments of the pilot area (for the optimisation of spraying route planning), while equipment testing and configuration setup took place in a strictly controlled environment and fully isolated location. The aircraft flow meter was always calibrated prior to each set of replicates upon ensuring that no air was trapped within the system, and the 2 pumps were calibrated twice during the experimental season, once at the start of the period prior to the commencement of the trials, and 20 days afterwards. The UAV's droplet spectra were measured as follows (droplet diameter at which % of the total spray liquid volume is made up of droplets smaller than that size): $D[v,0.1] = 137 \mu\text{m}$, $D[v,0.5] = 283 \mu\text{m}$, and $D[v,0.9] = 793 \mu\text{m}$. For the conventional application, a trailed air-assisted sprayer designed for bush and tree crops (Archimedes Turbo FS 1000, "Archimedes" G. Roumeliotis, Aridaia Pellas, Greece) was used. The sprayer was equipped with a 1000-L polyester tank, an 800-mm axial fan with a two-speed gearbox, and seven nozzles on each side. The nozzles were conventional hollow-cone TeeJet TXA 8002VK (yellow), with a nominal flow rate of 1.40 L/min at 1.0 MPa, while for all tests, the spray pressure was maintained at 1.0 MPa, with a forward speed of 6 km/h. The application volume was 450 L/ha. In every trial, the PTO speed was set to 540 rev/min, while the fan operated at 1620 rev/min, corresponding to a 1:3 fan ratio. The respective droplet spectra for the conventional air-assisted sprayer with these nozzles were the following: $D[v,0.1] = 170 \mu\text{m}$, $D[v,0.5] = 551 \mu\text{m}$, and $D[v,0.9] = 824 \mu\text{m}$.

2.2. Experimental design

The drone's performance was evaluated in three different application methods under open-field conditions, namely by flying over-row and leaving the last vine line as a buffer, and flying inter-row while using no buffer (meaning the UAV flew over the last corridor of the vineyard) and a single buffer line (not flying over the outer most corridor). In all these trials, the UAV was operating in different spraying settings (different altitudes Above Ground Level - AGL and aircraft speed). All flight parameters were decided and applied in the flight planning of the UAV interface (controller and integrated telemetry), thus modifying the aircraft's speed and altitude while the application volume was left unchanged (which translated to different flow rate as all trials were conducted with a predetermined application volume per area unit, namely 80 L/ha). Before the start of each spraying trial, an additional buffer area of at least 20 m was always sprayed (starting from the furthest, most internal line to minimise the contamination of the samplers from droplets from the start-up zone), to ensure the spraying UAV was not affected by start-up effects when entering the first sprayed line.

The experimental area was open and free of obstructions other than the target crop (vineyard), as any additional obstacles could influence airflow within the sampling area. Downwind of the directly sprayed zone, the ground consisted of bare soil, where collectors were placed to measure sedimenting spray drift. Ground collectors were positioned at

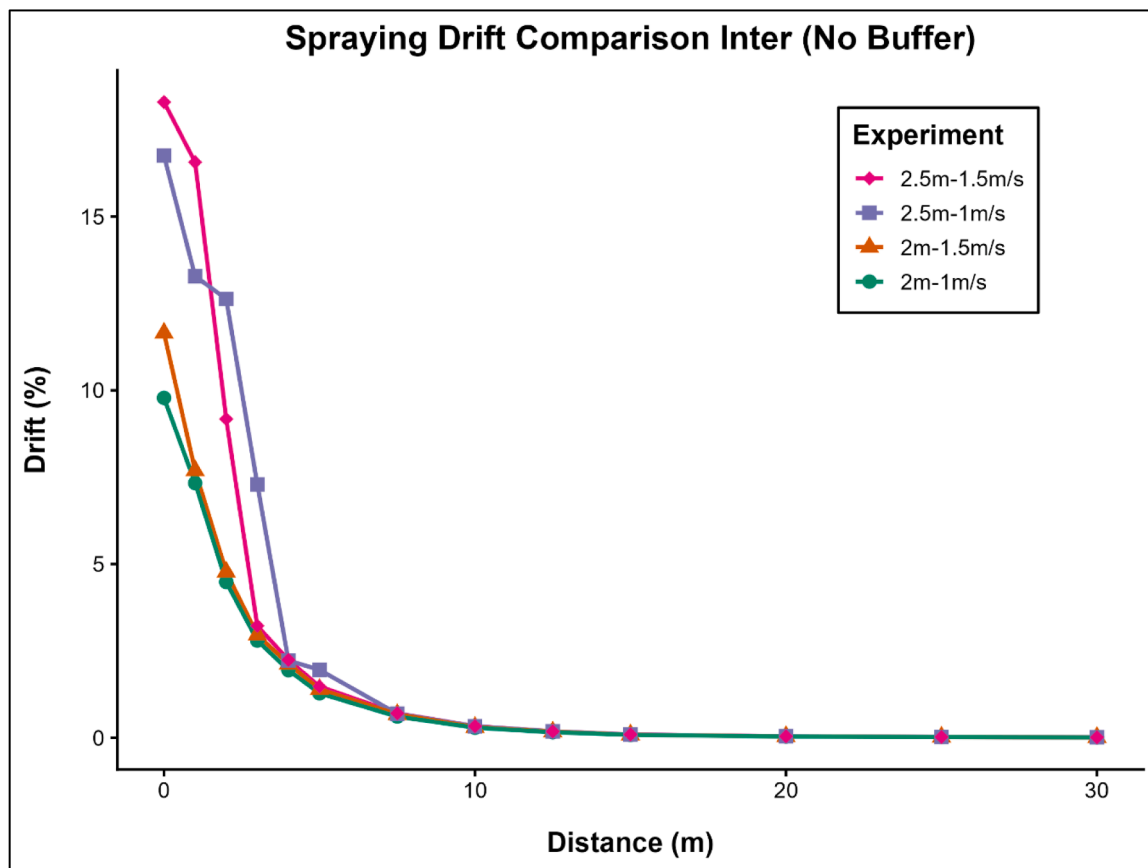


Fig. 4. Spray drift curves for inter-row application without buffer. drift percentage as a function of downwind distance for four UAV operational configurations (2.5 m–1.5 m/s, 2.5 m–1 m/s, 2 m–1.5 m/s, 2 m–1 m/s). Higher altitude and higher flight speed produced the highest drift at 0–5 m, with drift rapidly decreasing to near-zero levels beyond 10 m.

13 sampling distances on bare soil: 0, 1, 2, 3, 4, 5, 7.5, 10, 12.5, 15, 20, 25, and 30 m from the edge of the directly sprayed area (Fig. 1). These distances were measured from a parallel straight line located 1 m in front of the last plant row (half of the row spacing). At each sampling distance, three wooden laths were installed, each with an upper surface covered by Whatman Grade 1 filter paper (46×8 cm), resulting in 39 drift samples per replication. An overview of the experimental design and sampling points are provided in Fig. 2. All trials were carried out by predefined flight plans for each replicate, spraying the ten (10) outer downwind rows of the vineyard (accounting for each buffer strategy) along a distance of 60 m, in order to treat a surface of 1200 m^2 ($60 \text{ m} \times 20 \text{ m}$) (Fig. 3).

The total number of experimental trials that constitute a measurement and all tested configurations (sets of operational parameters) are presented in Table 1. Each iteration is replicated three times, resulting in a total of 36 measurements per dataset. Each set of three replicates for every treatment was conducted consecutively, and as close in time as possible, within a single day to obtain data under the most similar conditions.

2.3. Meteorological conditions

Weather conditions were measured continuously during each test using a portable ultrasonic anemometer, positioned near the test site 15 m upwind of the flight path (to avoid turbulence caused by the spraying drone's rotors). The sensor height was 1.5 m above ground, and measurements were recorded at 1 Hz. The vector perpendicular to the vine rows was measured as 40° (northeast). For each trial, the deviation of the wind direction from this perpendicular was calculated from those values, thus using the perpendicular to the sprayers line (90°) value as a

reference for convenience.

The field experiments were carried out based on thresholds adapted from the [22], which set general criteria on the conditions for spray measurements within and outside the field's boundaries. To this end, all measurements were carried out under the following conditions: ambient air temperature between 5°C and 35°C , wind speed at 1 m above the canopy of at least 1 m/s and 3 m/s and the mean wind direction at $90^\circ \pm 30^\circ$ relative to the spray track (with no $>10\%$ of wind-speed readings outside that space). The averaged wind speed and direction values for each trial can be found in Table 2. In addition, the restriction that relative humidity shall remain below 70 % for the duration of the trial was also imposed. If the ambient temperature dropped below 5°C or rose above 35°C , or if relative humidity exceeded 70 %, the trial was deemed invalid and was set to be repeated under suitable environmental conditions. During the experimental period, the temperature criterion was exceeded only once (due to an extensive heatwave in Greece that caused temperatures to reach 35°C even early in the morning), which required a singular repetition to be repeated on a different day.

2.4. Sample analysis

The spray liquid consisted of clean water mixed with the dye tracer E-102 Tartrazine (85 % w/w) at a concentration of approximately 4 g/L for the conventional sprayer. The application volume commonly used in similar vineyards, and thus adopted in this study, was 600 L/ha. Therefore, to achieve an equivalent dye application rate with the spraying UAV, which applied 80 L/ha, the solution used for the UAV was adjusted accordingly to maintain the same tracer concentration per hectare, namely 30 g/L.

Before each test, a blank filter paper sample was placed in the

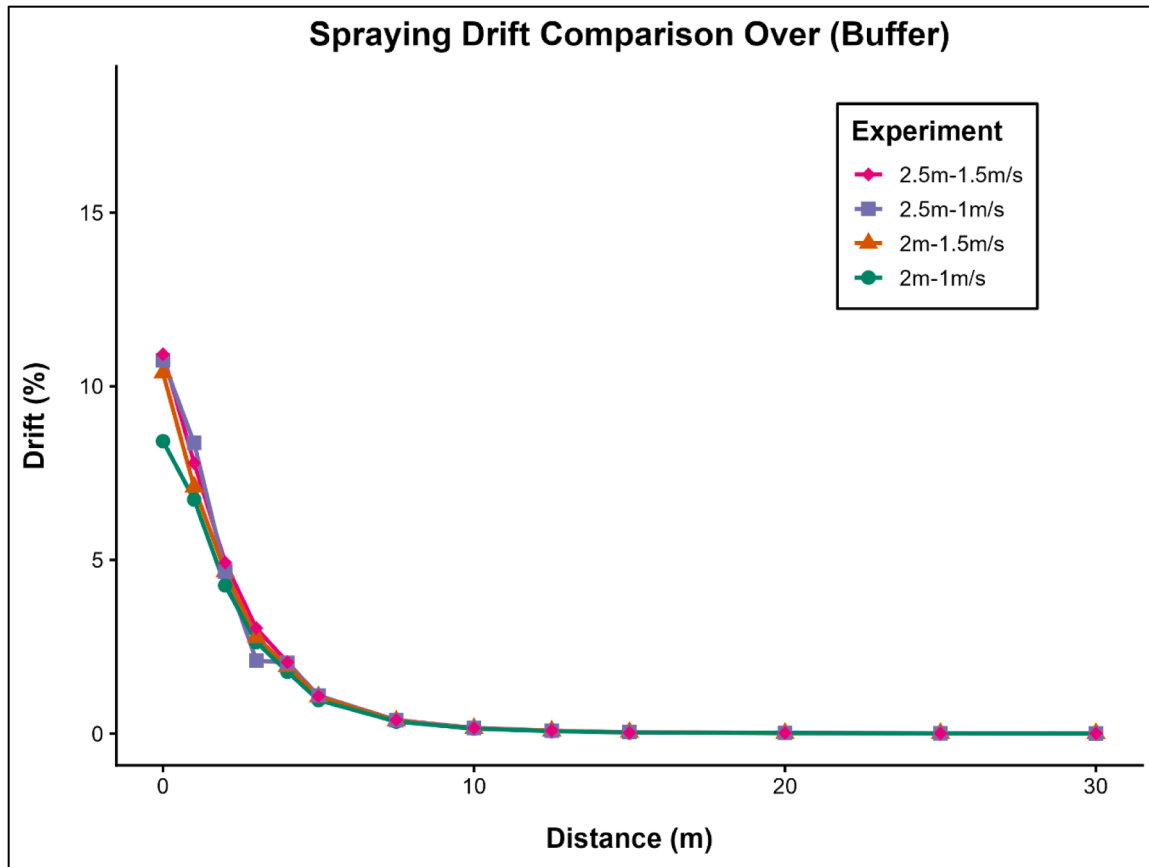


Fig. 5. Spray drift curves for over-row application with buffer. effect of altitude and flight speed on drift during over-row spraying, with a 20 m buffer applied before entering the sampling zone. Drift values at 0 m were lower than in the no-buffer case, and drift fell below 1 % by approximately 5 m downwind.

sprayed area and collected immediately before spraying commenced. Two samples of the spray liquid were also collected directly from a nozzle (one at the beginning and one at the end of the trial) to determine the exact tracer concentration at the nozzle outlet for each trial. After collection, all samples were transferred to the laboratory for analysis. Tartrazine concentrations in soil and air collectors were quantified using a Shimadzu UV-2600i Plus spectrophotometer operating at a wavelength of 426 nm.

Spray tracer deposits were extracted from the samples using deionized water. Depending on the sample and how far it was from the application area (thus expected to yield lower concentration values), different volumes of deionised water were added to ensure that the spectrophotometer reading fell within the linear range of the calibration curve for Tartrazine. The spectrophotometer reading was then related to the tracer quantity in solution through this calibration curve. Using the spectrophotometer reading, the calibration factor, the collector surface area, the spray concentration, and the volume of dilution water, the amount of spray deposit per unit area was calculated as follows:

$$drift_{dep} = \frac{(\rho_{smp} - \rho_{blk}) \cdot F_{cal} \cdot V_{dil}}{\rho_{spray} \cdot A_{col}}$$

Where:

- drift_{dep} = spray drift deposit (μL/cm²)
- ρ_{smp} = spectrophotometer reading of the sample (Abs)
- ρ_{blk} = spectrophotometer reading of the blanks (collector + deionized water) (Abs)
- F_{cal} = calibration factor (μg/L)
- V_{dil} = volume of dilution liquid (L)
- ρ_{spray} = spray concentration of tracer (g/L)

A_{col} = collection area of the spray drift collector (cm²)

From the spray drift deposition value, the percentage of spray drift retrieved by the collector can be calculated by relating the measured deposition to the amount applied in the field on the same unit area, using the following formula:

$$drift\% = \frac{drift_{dep} \cdot 10^4}{\beta_v}$$

where β_v is the spray application volume in liters per hectare (L/ha).

3. Results

3.1. Drift curves

3.1.1. Drift curves for inter-row application without buffer

Fig. 4 shows the drift curves for inter-row spraying without any buffer applied. The highest drift levels were recorded at 2.5 m AGL with a flight speed of 1.5 m/s, where drift reached approximately 18 % at the closest sampling distance downwind. Lowering the flight altitude to 2.0 m reduced drift substantially, confirming the effect of downwash reinforcement at lower heights. Similarly, reducing UAV speed from 1.5 m/s to 1.0 m/s resulted in significantly lower drift values across the first 5 m, due to the production of larger droplets (due to lower flow – as speed is connected to flow under constant application volumes per area) and reduced horizontal momentum. Across all configurations, drift dropped sharply within the first 5 m and approached near-zero levels beyond 10 m downwind. This rapid decay follows the expected exponential reduction pattern for UAV spraying, where initial droplet sizes and rotor-induced turbulence dominate early dispersion.

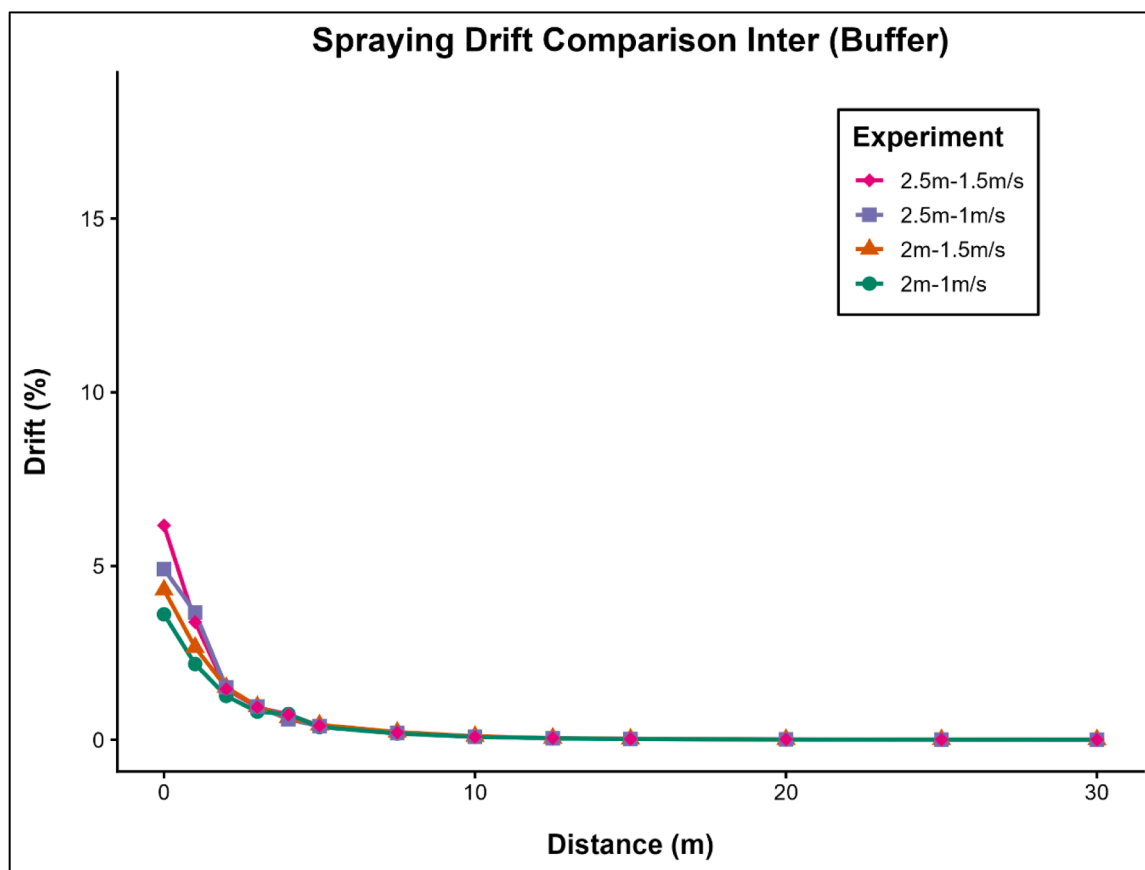


Fig. 6. Spray drift curves for inter-row application with buffer. drift values were substantially reduced relative to the no-buffer configuration, with maximum drift at 0 m ranging around 5 %.

3.1.2. Drift curves for over-row application with buffer

For over-row applications with a single vine line as buffer, overall drift values were lower than in the inter-row no-buffer case (Fig. 5). Maximum drift at 0 m ranged between 10 % and 11 %, with all treatments converging to below 2 % at 5 m. Differences between altitude and speed combinations remained consistent with the previous case. Higher altitude produced higher drift, while higher speed slightly increased dispersion near the emission point. The introduction of the buffer allowed the droplets to intercept an additional vine line before exiting the field's boundary, thus reducing drift as expected.

3.1.3. Drift curves for inter-row application with buffer

Fig. 6 presents the inter-row spraying with an additional buffer (the outer-most corridor not crossed by the UAV). Compared with the no-buffer configuration, drift values at closest distance were reduced by approximately 60 %. Maximum drift for the least favourable setting (2.5 m, 1.5 m/s) was around 6 %, almost one-third-of the recorded drift for the same application without the buffer corridor. Differences between treatments were less pronounced in this configuration. All curves showed similar decay, with drift dropping below 1 % by 4 m and remaining negligible beyond 10 m.

3.3.4. Average drift comparison across all configurations

The aggregated comparison (Fig. 7) highlights the dominant effect of altitude on drift generation. Treatments conducted at 2.5 m AGL consistently produced the highest drift values, while the lowest drift was achieved at 2.0 m and 1.0 m/s. The effect of speed was also evident: the 1.5 m/s flights yielded higher drift than the 1.0 m/s flights at all distances. Across all treatments, drift remained concentrated in the first 3 to 5 m, and beyond 10 m drift levels were consistently below 0.5 percent. These results align with theoretical expectations for UAV

spraying, where lower altitude intensifies rotor downwash and improves canopy interception, and where lower flight speed tends to increase droplet size and reduce horizontal momentum. Together, these parameters can potentially limit off-field droplet displacement and spray drift.

3.3.5. Average drift curve for the conventional sprayer

Finally, the conventional airblast sprayer results are presented in Fig. 8. Across almost all replicates (with the exception of the two least favourable UAV trials conducted at a 2.5 m altitude with no buffer) the conventional sprayer consistently produced higher drift, particularly at the closer sampling distances, reaching almost 17.5 % at the first sampling location.

3.2. Windrose diagrams

The effect of wind direction and speed, widely considered the single most impactful environmental parameters for spray drift, are presented in the form of Windrose diagrams (3 replicates average), divided in different zones based on their proximity to the application area (Figs. 9,10, and 11).

Interestingly, windspeed demonstrated little effect on the drift values on the Spraying UAV trials. The highest average recorded wind speed (2.4 m/s) across the spraying UAV trials (namely 2.5 m / 1,5 m/s, inter-row no buffer) exhibited the highest drift values, but it was followed by a similar application (namely 2.5 m / 1.0 m/s, inter-row no buffer) under the lowest wind speed recorded (at 1.5 m/s wind speed). This can potentially indicate that, while operating within "appropriate" environmental conditions (<3 m/s wind speed), operational settings of the aircraft and application strategy are much more impactful than wind speed. Finally, the Windrose diagram for the average wind speed during the conventional sprayer trial (based on three replicates) is presented in

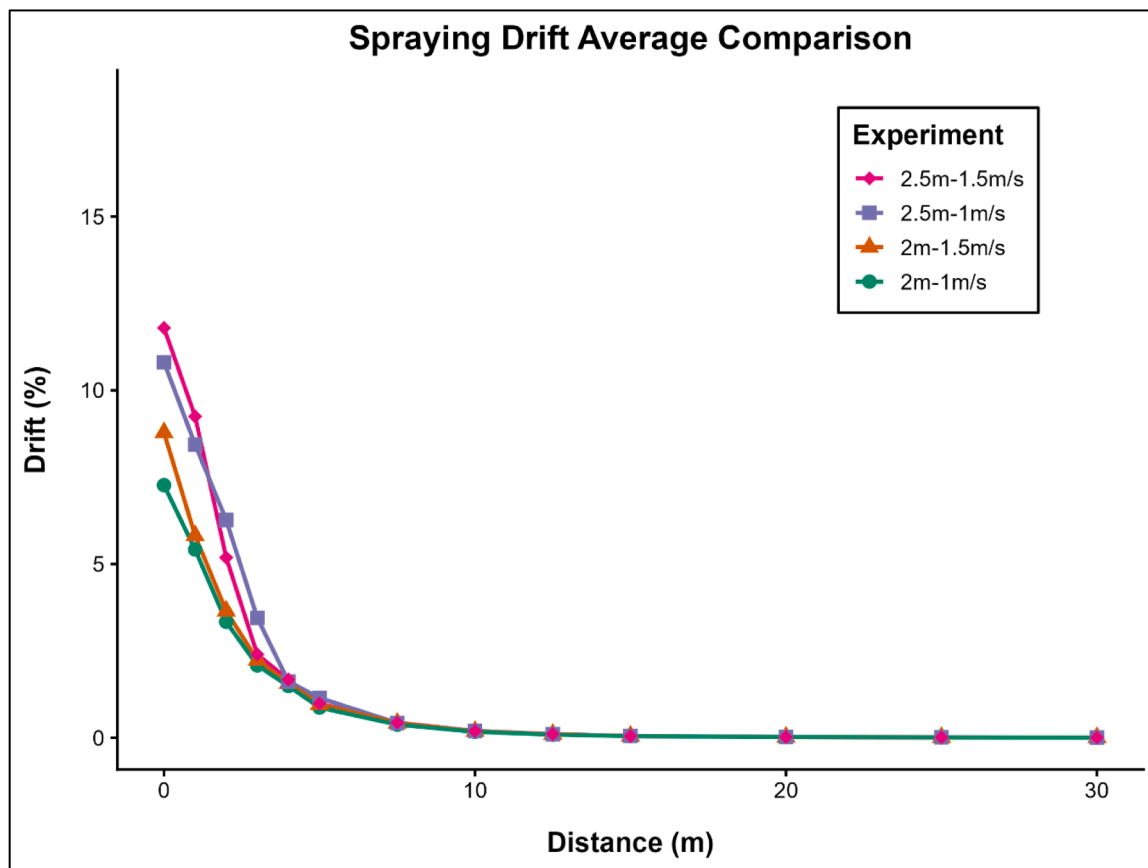


Fig. 7. Average spray drift comparison across all configurations. mean drift curves showing the combined effect of altitude and flight speed. Treatments at 2.5 m AGL consistently produced the highest drift, whereas flights at 2.0 m and 1.0 m/s yielded the lowest drift.

Fig. 12, illustrating the same trends observed in the drift curves. Interestingly, the averaged drift values for the first six sampling distances (0–5 m) exceed those recorded for all UAV trials, even though some UAV configurations (particularly those at 2.5 m altitude and no buffer) showed higher drift at the closest distance (0 m, the collector nearest the field boundary).

4. Discussion

The experimental results confirmed several consistent patterns regarding the influence of UAV operational settings on spray drift behaviour in vineyards. Across all trials, drift was highly concentrated at the emission point and declined rapidly within the first few metres downwind, consistent with the exponential decay typically observed in UAV spraying studies [4,18]. Within this general pattern, altitude, speed and the use of a buffer zones emerged as the key determinants of drift magnitude and variability.

Altitude was the strongest determinant of drift across all tests. Increasing AGL from 2.0 m to 2.5 m increased drift at the emission point by approximately 30 % - 70 %, depending on the configuration. Comparable results have been documented in previous orchard and vineyard UAV studies, where flight height has consistently been identified as a primary driver of off-target spray movement [17,20]. This behaviour can be attributed on the reduced downwash intensity at higher altitudes, which weakens the downward confinement of droplets and increases their exposure to crosswind. This agrees with the theory that reduced lateral air entrainment and the powerful downwash generated by rotor-induced airflow acting as a barrier that prevents droplets from being swept away by the wind, can limit off-target displacement in UAV applications compared to the stronger, outward-directed plume of the airblast system. As illustrated in Fig. 13, UAV applications generated

substantially lower drift than the conventional air-assisted sprayer, likely because the drone's more localised spray release and lower overall airflow momentum produce a narrower, more contained plume that limits off-target movement compared with the broader, high-energy discharge of the airblast system.

Flight speed had a secondary but systematic effect. Operating at 1.5 m/s produced 10 % - 20 % higher drift at the closest to the application area sampling distance (0 m, namely 1 m from the final vine line) compared to the "slower" trials of 1.0 m/s. This can be attributed to two mechanisms: (1) higher forward speed tends to generate slightly finer droplets, and (2) greater horizontal momentum increases initial droplet displacement. Both mechanisms increase the likelihood of droplet transport beyond the treated zone, which is consistent with findings for conventional sprayers [8]. In the UAV spraying context, higher horizontal velocity also reduces the residence time of droplets within the downwash column, further decreasing canopy interception.

The use of an additional buffer line (for over-row applications) or corridor (for inter-row applications) significantly reduced drift across all operational configurations. Fig. 13 provides an aggregated schematic illustrating this effect, showing that spray drift from UAV applications can be substantially mitigated through appropriate application strategies and drift control practices.

Differences between inter-row and over-row spraying were present but less pronounced. Inter-row spraying without buffer generated the highest drift levels, likely because the UAV's downwash interacts less directly with the vine canopy when flying between rows. Over-row application potentially benefited from increased canopy interception and turbulent dissipation within the crop structure. Once the buffer was applied, drift differences between the two application strategies narrowed considerably. The distribution analysis across configurations further corroborated the mechanistic trends observed in the drift curves.

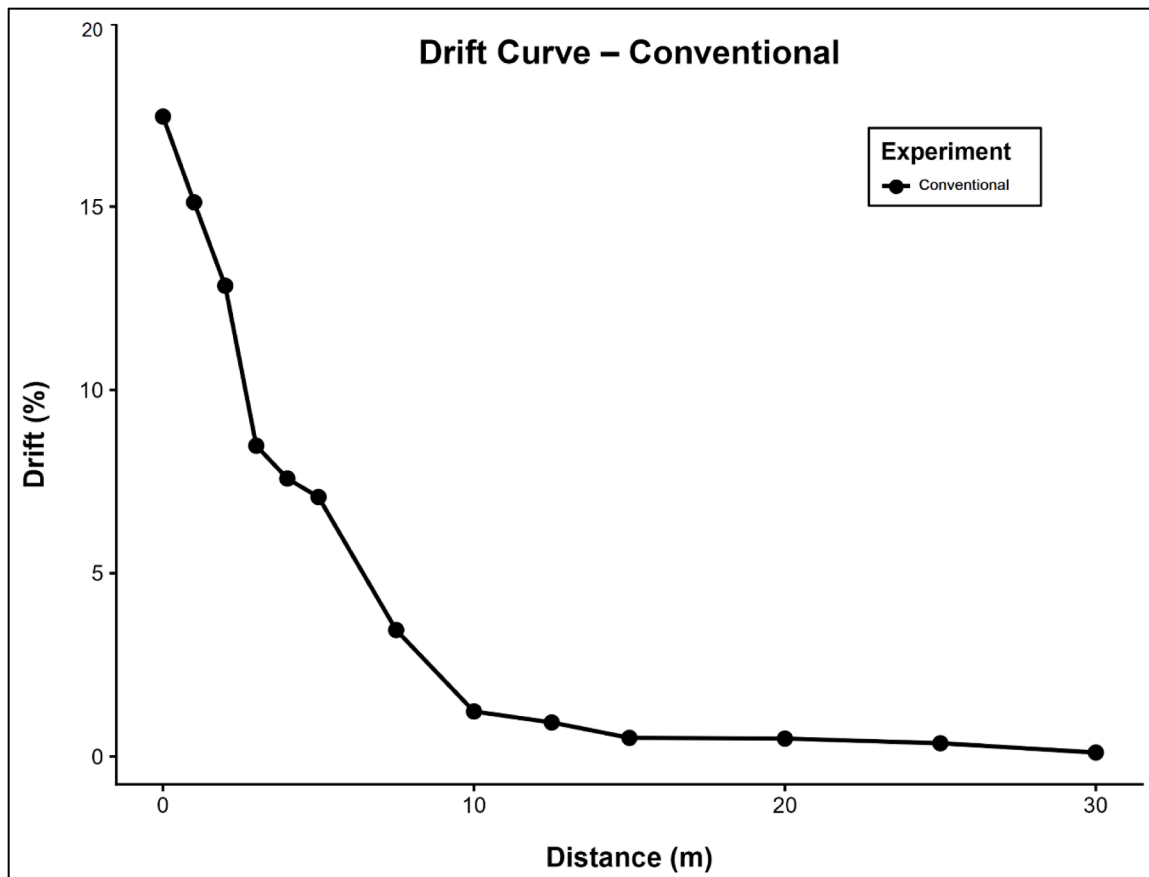


Fig. 8. Drift curve of the conventional sprayer used in the vineyard where this study was conducted.

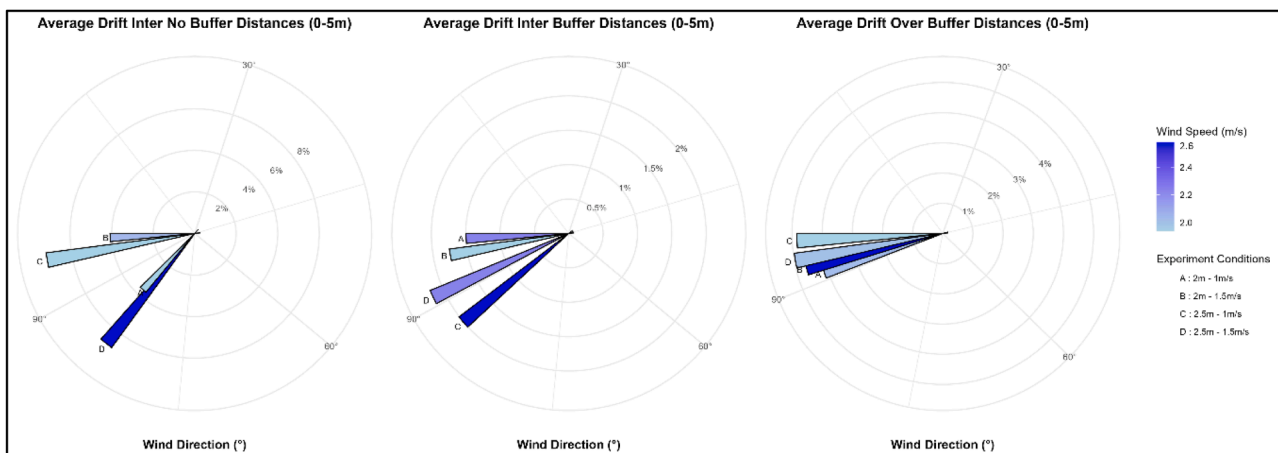


Fig. 9. The Windrose diagram for the sampling distances of 0 m to 5 m from the application area.

Higher-altitude flights exhibited greater variability and more pronounced outliers, reflecting increased susceptibility to crosswind and reduced control over droplet trajectories. In contrast, lower altitude and reduced speed produced tighter drift distributions, consistent with stronger downwash confinement and larger droplet formation (Fig. 14).

This behaviour can also be attributed to the droplet spectra and the expected changes of the produced droplets under different operational configurations, namely different flow rates which change based on pump pressure. Increasing pump output in a spraying system, while maintaining the same number and type of active nozzles leads to systematic changes in spray formation. Greater discharge per nozzle is

achieved by through a higher operating pressure (consistent with a square-root relationship between flow rate and pump pressure). The accompanying increase in liquid exit velocity promotes atomisation, yielding smaller droplets and a more concentrated spray cloud. Although these conditions can enhance target coverage and improve deposition across different canopy levels, they also elevate drift potential, as finer droplets are more susceptible to be transported off-target (outside the field boundaries) by air movement. Interestingly, the highest average drift was observed in treatments combining lower flight speed and higher altitude (1 m/s and 2.5 m, respectively). A possible explanation is that, although smaller droplets are more susceptible to

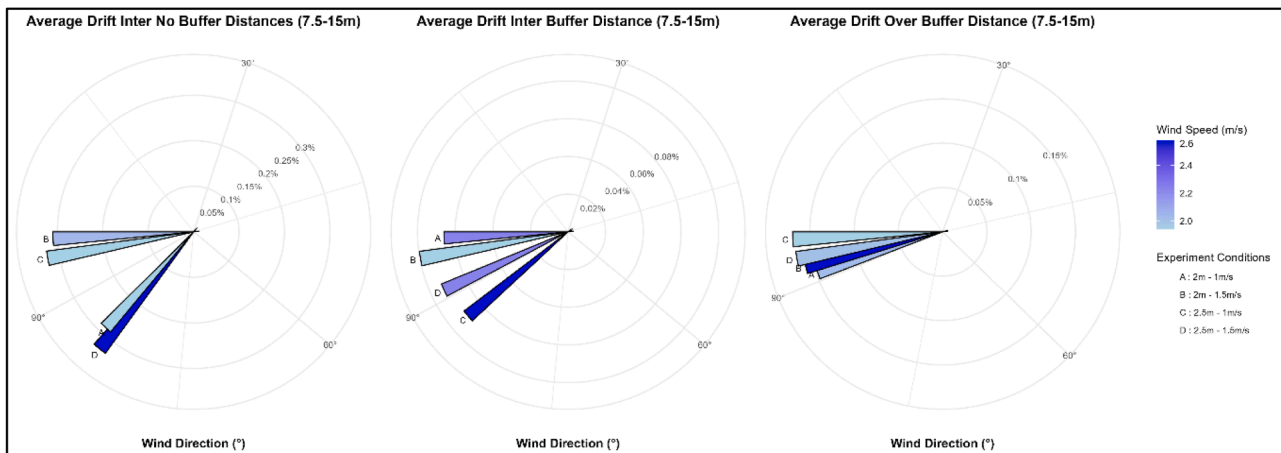


Fig. 10. The Windrose diagram for the sampling distances of 7.5 m to 15 m from the application area.

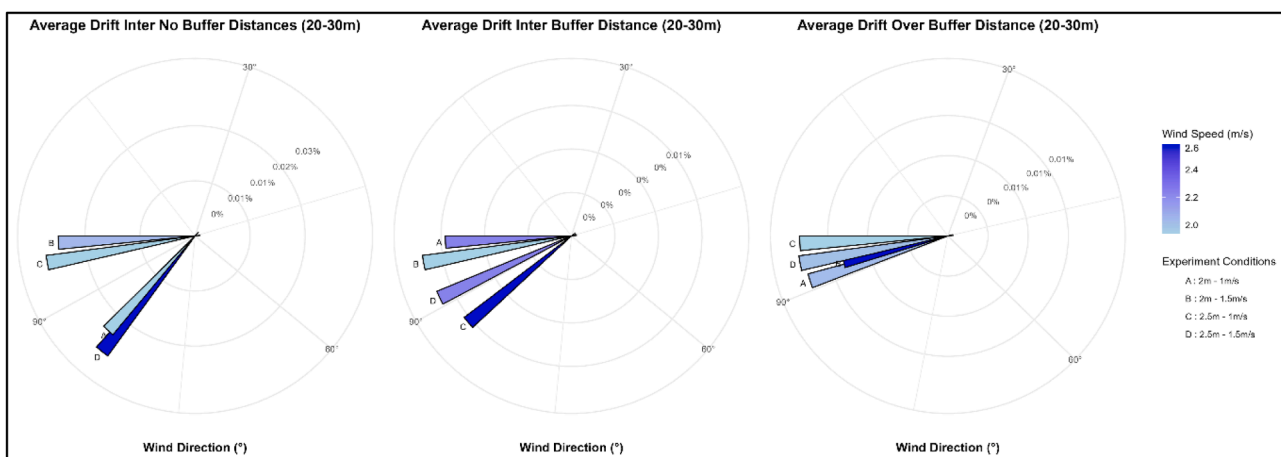


Fig. 11. The Windrose diagram for the sampling distances of 20 m to 30 m from the application area.

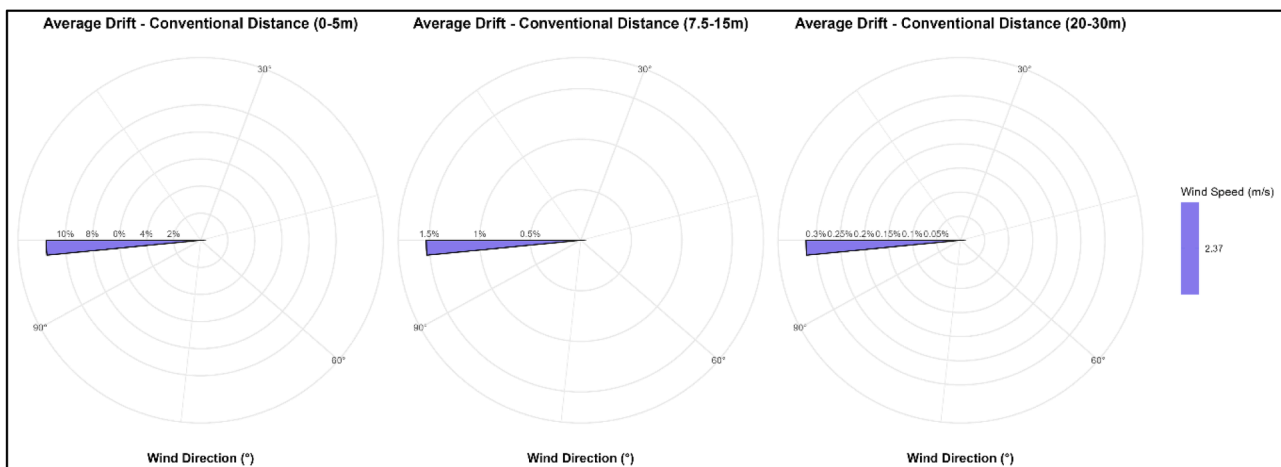


Fig. 12. The Windrose diagram for the 3 sampling zones (based on distances from the application area).

wind transport, the drone’s downwash may also restrict their movement, limiting their displacement by ambient wind currents (Fig. 15).

Overall, the findings demonstrate that UAV spray drift can be substantially reduced by operating at lower altitudes, reducing flight speed and incorporating a buffer zone around the field’s boundaries. Under optimal settings (inter-row, 2.0 m AGL, 1.0 m/s, with buffer of a single

vine corridor), drift levels became negligible beyond 10 m downwind, indicating that UAV sprayers can meet drift-reduction requirements for specialty crops such as vineyards. These results reinforce the importance of downwash-assisted deposition and stable flow conditions in achieving safe, efficient and environmentally responsible UAV spraying.

Average Drift Curve by Application Strategy

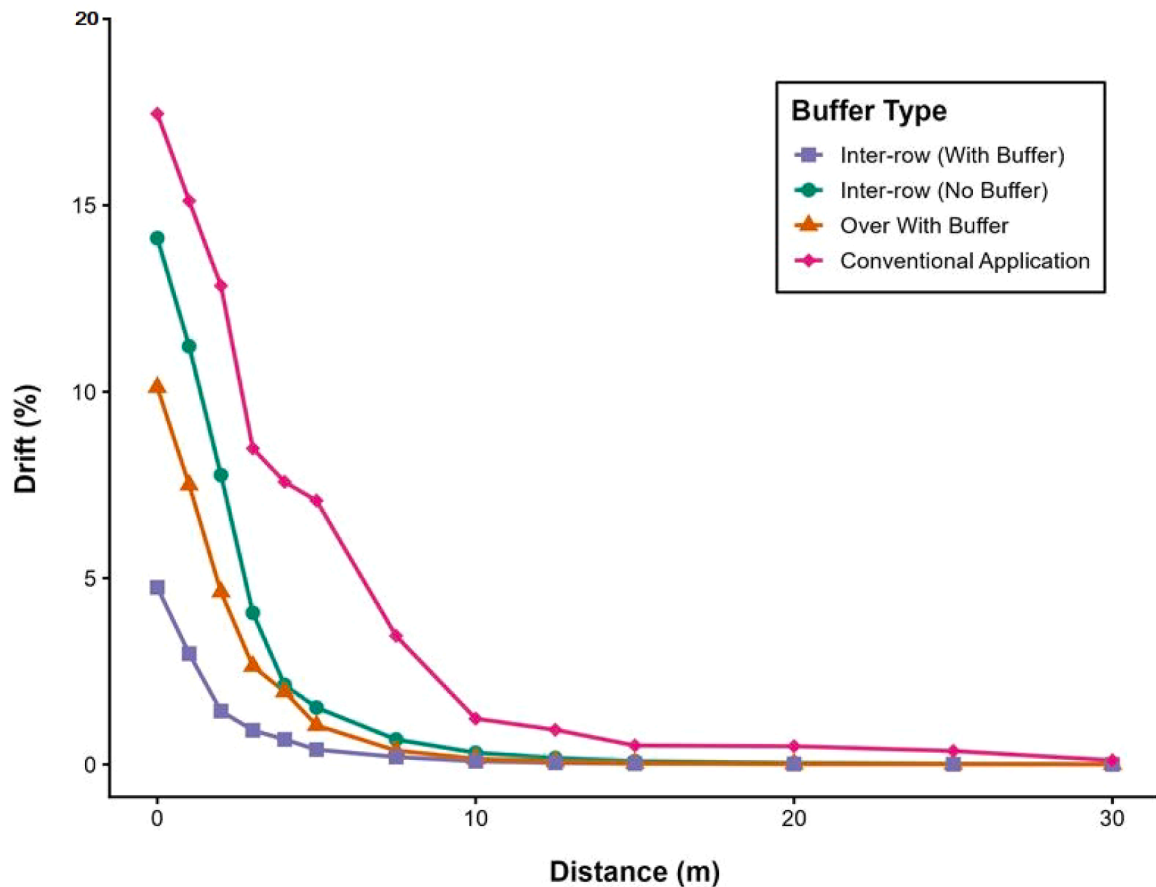


Fig. 13. An overview of all spraying application strategies (average) comparing the UAV applications to those of the air-assisted sprayer.

5. Conclusions

This study provides quantitative insights into the impact of different operational configurations for spraying UAVs on spraying application performance. The findings aim to support autonomous flight planning and more efficient smart-spraying operations, by informing the selection and optimisation of flight parameters prior to mission design and execution. To this end, this study provides a detailed characterisation of UAV spray drift in a vineyard open-field environment and demonstrates that operational parameters play a decisive role in off-target droplet movement. Flight altitude was the strongest determinant of drift, with 2.5 m AGL producing markedly higher drift than 2.0 m AGL. Higher flight speed (1.5 m/s) further increased drift, although to a lesser extent. Moreover, for the trials conducted within “greenlit” environmental parameters (namely wind direction almost perpendicular to the path of the sprayer, and a wind speed that ranges from 1.5 m/s to 2.5 m/s for most replicates, the conventional sprayer used in this study as a reference produced significantly higher spray drift, compared to UAV trials that used any form of buffer practice.

Optimising spraying UAV application strategies and applying proper buffer lines can potentially decrease drift by up to 60%. Across configurations, flight altitude and the presence of a buffer consistently emerged as the most influential factors: lower altitudes and the use of one or more buffer rows significantly reduced off-target deposition within the measured range. Inter-row spraying without a buffer generated the highest drift levels due to weaker canopy interaction and proximity of the nozzles to the drift sampling area (off-field), whereas over-row spraying benefited from increased canopy interception and the

presence of an additional vine line acting as a “barrier”.

Across all tested configurations, drift declined rapidly and became negligible beyond 10 m downwind, indicating that UAV sprayers can achieve low drift levels under suitable operating conditions. Operating at lower altitudes, reducing flight speed, and incorporating a buffer represent practical, evidence-based measures for minimising off-target losses. Buffer zones are widely considered as a very simple and yet effective method of drift mitigation in conventional sprayers, and our current findings also confirm their effectiveness in the case of spraying drones. Compared with the conventional sprayer, UAV applications with appropriate buffer strategies achieved substantially lower drift at both near-field and far-field distances, confirming their potential as a lower-drift alternative for vineyard plant protection. These findings provide actionable guidance for vine growers, UAV operators, and regulators and support the safe and effective deployment of UAV spraying technologies in specialty crops such as vineyards.

Ethics in publishing statement

I testify on behalf of all co-authors that our article submitted followed ethical principles in publishing.

All authors agree that:

This research presents an accurate account of the work performed, all data presented are accurate and methodologies detailed enough to permit others to replicate the work.

This manuscript represents entirely original works and or if work and/or words of others have been used, that this has been appropriately cited or quoted and permission has been obtained where necessary.

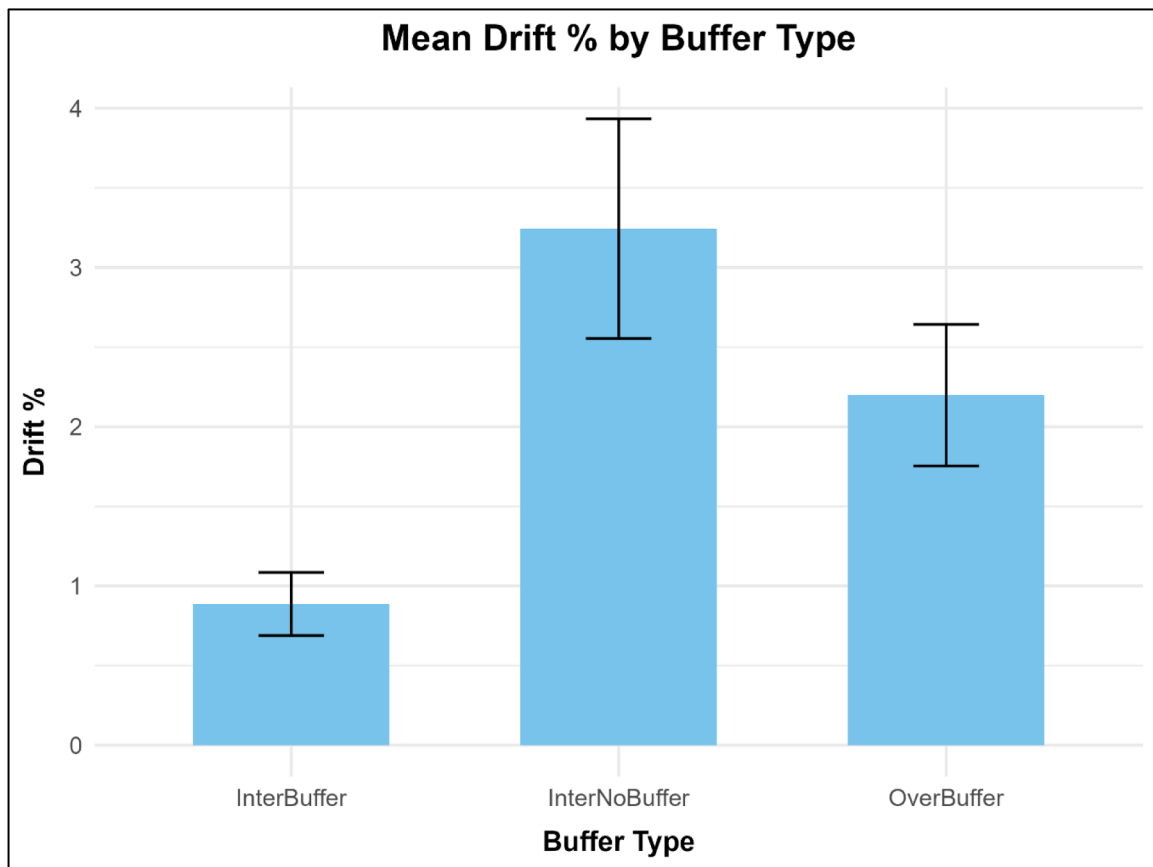


Fig. 14. Mean spray drift percentage for each buffer configuration.

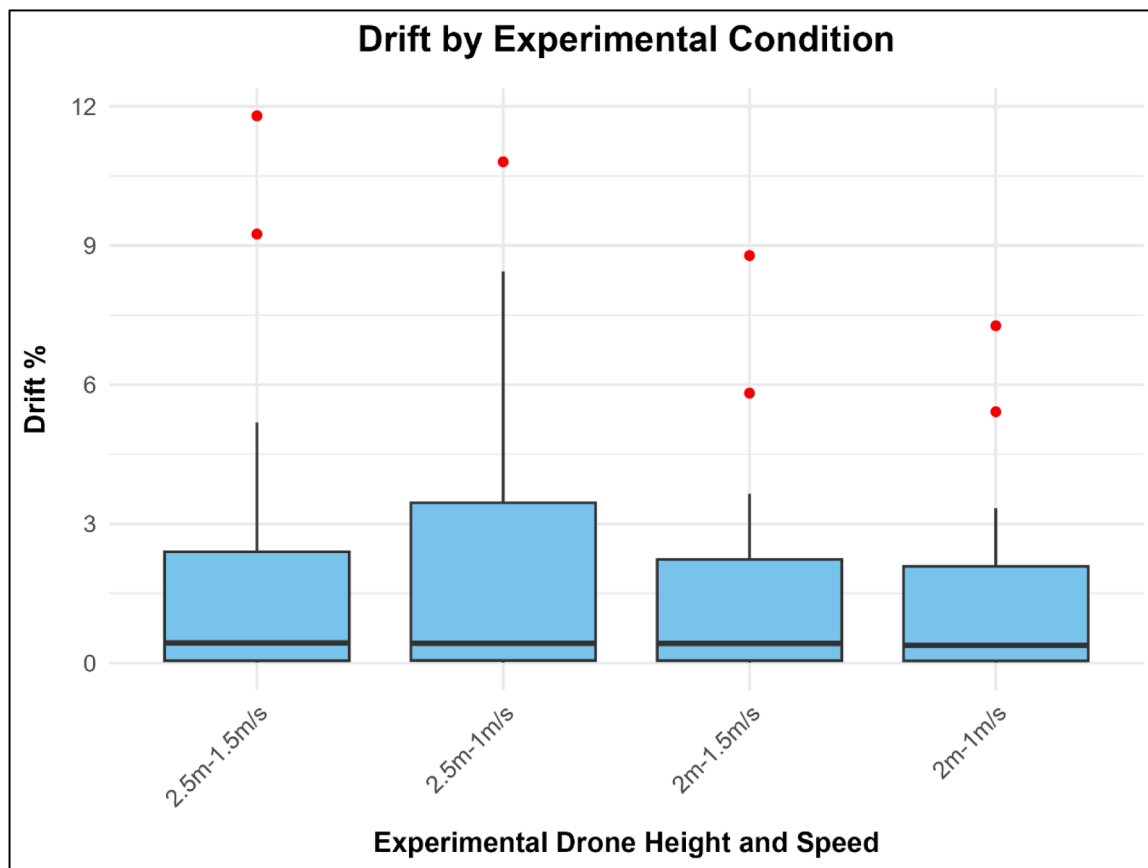


Fig. 15. Boxplot distribution of drift across the four operational flight settings.

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All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

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CRedit authorship contribution statement

Vasilis Psiroukis: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Aikaterini Kasimati:** Writing – review & editing, Writing – original draft,

Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Konstantinos Nychas:** Writing – original draft, Visualization, Validation, Software, Formal analysis, Data curation. **Evangelos Anastasiou:** Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Athanasios Balafoutis:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Spyros Fountas:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. Dr. Spyros Fountas is an editor-in-chief for Smart Agricultural Technology and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Data availability

Data will be made available on request.

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