Rev. FCA UNCuyo. 20XX. XX(X): XXX-XXX. ISSN (en línea) 1853-8665.

Pesticide drift: comparing spraying systems under variable field climatic conditions

Deriva de pesticidas: un estudio comparativo entre sistemas de aspersión bajo condiciones climáticas variables de campo

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Originales: *Recepción:* 19/11/2023- *Aceptación:* 12/09/2024

Abstract

Safe pesticide application must ensure efficacy in pest control while minimizing environmental and human health risks. This study investigated pesticide potential drift by comparing ground and aerial spraying systems under different climatic conditions. The research was conducted in Rio Verde, Goiás, Brazil, using a randomized block experimental design with 10 repetitions and a 2 x 2 split-plot scheme, considering spraying systems and climatic conditions as factors. *Favorable* and *Unfavorable* conditions were determined by relative air humidity, temperature, and wind speed. Aerial spraying was performed using a Cessna aircraft, while terrestrial spraying was done using a self-propelled Montana Parruda sprayer. Variables assessed included Volumetric Median Diameter (VMD), droplet density (DEN), and target coverage. Results revealed that aerial spraying has a higher drift potential, exceeding 180 m, compared to terrestrial spraying, limited to 90 m under unfavorable conditions. Although terrestrial spraying produces larger droplets, its shorter distance to the target and reduced speed minimize lateral movement, limiting drift potential. Droplet density and non-target area coverage were low for both systems, (0.1%). Under ideal conditions, aerial spraying is more efficient, but both methods require rigorous safety measures to prevent contamination risks. This study underlines the importance of considering droplet size and specific environmental conditions when choosing a spraying system, contributing to safer and more efficient agricultural practices.

Keywords
aerial application • terrestrial spraying • application technology

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RESUMEN

La aplicación segura de pesticidas en grandes cultivos es una preocupación crucial para garantizar la eficacia en el control de plagas y al mismo tiempo minimizar los riesgos ambientales y para la salud humana. En este contexto, este estudio investigó la posible deriva de pesticidas comparando sistemas de fumigación terrestre y aérea en diferentes condiciones climáticas. La investigación se realizó en Rio Verde, Goiás, Brasil, utilizando un diseño experimental de bloques al azar con 10 repeticiones. Se adoptó un esquema de parcelas divididas 2 x 2, considerando los factores de los sistemas de aspersión y las condiciones climáticas. Las condiciones favorables y desfavorables se determinaron mediante parámetros como la humedad relativa del aire, la temperatura y la velocidad del viento. La aspersión aérea se realizó mediante una aeronave Cessna, mientras que la aspersión terrestre se realizó mediante un aspersor autopropulsado Montana Parruda. Las variables evaluadas en este estudio incluyeron el diámetro medio volumétrico (VMD), la densidad de gotas (DEN) y la cobertura objetivo. Los resultados revelaron que la aspersión aérea tiene un mayor potencial de deriva, alcanzando distancias superiores a 180 m, en comparación con la aspersión terrestre limitada a 90 m en condiciones desfavorables. Aunque la pulverización terrestre produce gotas más grandes, su distancia más corta al objetivo y su velocidad reducida minimizan el movimiento lateral, lo que limita el potencial de deriva. La densidad de gotas y la cobertura del área no objetivo son bajas para ambos sistemas y se mantienen por debajo del 0,1%. En condiciones ideales, la fumigación aérea es más eficiente, pero ambos métodos requieren medidas de seguridad rigurosas para prevenir riesgos de contaminación. Este estudio enfatiza la importancia de considerar no solo el tamaño de las gotas sino también las condiciones ambientales específicas al elegir un sistema de aspersión, lo que contribuye a prácticas agrícolas más seguras y eficientes.

Palabras clave
aplicación aérea • fumigación terrestre • tecnología de aplicación

INTRODUCTION

Pesticides have been used in agriculture for centuries to protect crops against pests, diseases, and weeds (4). Despite studies demonstrating that their use can be reduced by combining other control methods, such as biological control (14), these products are still necessary for agriculture, especially considering large-scale cultivation and crop productive potential (16). This dependence on pesticides is evident in numbers. The European Union, Brazil, the United States, and China, worldwide major food producers, used approximately 827 million, 831 million, 1.2 billion, and 3.9 billion pounds of pesticides in 2016, respectively (5, 8, 25). This scenario remains for most food-producing countries (22). Therefore, adjusting the spraying system and minimizing pesticide impact on non-target organisms, is crucial.

Pesticide-safe application should consider four pillars: the formulated product, target, timing, and spraying system. The first three pillars directly affect system choice. Consequently, all 4 pillars should be analyzed jointly. Once these pillars are properly adjusted, efficient applications assure minimum non-target organism contamination (1). When these components are not well dimensioned, drift and evaporation, two main contamination pathways, are considerably increased. The adopted spraying system and the environmental conditions during application (timing) strongly influence risk potential (2, 3).

Pesticide drift is the unintentional transport of spray droplets away from the control target. Often, this transport leads to contamination of urban areas, forests, and rivers (3). Drift can be studied as primary and secondary drift. Primary drift results from the transport of an active ingredient away from the intended area, after passing through the spray nozzle, due to airflow during application (3). Secondary movement occurs after pesticide application due to chemical volatilization (15). Unlike secondary drift, many factors resulting in primary movement are largely under human control (3).

Studies on pesticide drift often focus on herbicide application risks given the possibility of intoxicating neighboring crops or native forests (3). Recently, this issue has gained attention given soybean cultivars resistant to dicamba and 2,4-D. These herbicides belong to the auxin mimics class, and the high sensitivity of dicotyledonous crops, including non-resistant soybeans, has increased crop damage in non-target areas. These reports are more frequent for dicamba (3). For example, in 2017, the USA reported 2708 cases of dicamba drift-induced injuries (21) while in Brazil, auxin herbicides stand as the main reported contamination in non-target areas. Between 2018 and 2021, 431 positive cases of auxin herbicide drift were recorded in the state of Rio Grande do Sul (9).

Although many studies address drift, associating this practice with contamination of neighboring crops, urban areas and native forests deserves particular investigation given human health and environmental safety. In Brazil, 2021 recorded 30 cases of pesticide drift in urban areas. Of these cases, 21 were caused by aerial applications of fungicides or insecticides (9). In Rio Verde, Goiás, 120 students were hospitalized due to drift caused by the aerial application of [thiamethoxam + lambda-cyhalothrin] (19).

Concerning human and environmental safety, Law N° 19423 of July 26, 2016, published in the Official Gazette on August 4, 2016, establishes restrictions on aerial spraying considering minimum distance from non-target locations: 500 m from urban perimeters and 250 m for public water reservoirs. For terrestrial sprayings, a minimum distance of 100 m is established from the urban perimeter, 200 m for public water reservoirs, and 50 m for isolated dwellings and animal clusters. Aerial application restrictions are stronger since droplet size and target distance may increase aerial drift compared to terrestrial spraying (2).

Despite restrictions, drift can reach greater distances. Even for primary drift, where the applicator can control some factors, drift still brings uncertainties during pesticide applications. Consequently, more studies should assess real drift, considering interactions between different spraying systems and environmental conditions. These studies are even more relevant in tropical conditions given higher frequency of unfavorable application conditions like high temperatures, lower relative humidity, and wind gusts (10). To facilitate drift deposit measurement processes, some researchers collect deposits on a drift test bench (11, 20) or in wind tunnels (6). Despite their advantages, these indirect methods cannot reproduce real aerial applications, and comprehensive field studies must be conducted (2). In this context, we studied the potential drift of ground and aerial spraying systems and the relationship between these systems and environmental conditions during field trials, identifying possible shortcomings in the current restrictions for pesticide spraying.

Materials and methods

The experiment was conducted in the municipality of Rio Verde (Goiás), Brazil (17°46'34.5" S 51°01'81.1" W). The region's climate is classified as B4 rB'4a' (humid; slight water deficiency; mesothermal; summer evapotranspiration less than 48% of the annual evapotranspiration), according to Thornthwaite (1948).

The experiment was conducted in a randomized complete block design with 10 replications. A 2 x 2 split-plot design was adopted to identify interactions between ground and aerial spray systems and climatic conditions during application. The climatic factor defined the main plots, while the spray system was defined in subplots. Two climatic conditions were considered, one *Favorable* and the other *Unfavorable*. Factor randomization in subplots was done by randomly selecting application moments for *Favorable* and *Unfavorable* classes. The parameters relative air humidity, instantaneous temperature, and wind speed determined *Favorable* and *Unfavorable* conditions (table 1, page XXX). Climatic data were obtained using an INSTRUTHERM THAL-300 thermo-hygro-anemometer. A wind direction indicator (windsock) was installed in the experimental area to guide application direction.

Table 1. Climatic conditions during spraying with the different equipment.

Tabla 1. Condiciones climáticas durante la pulverización con los diferentes equipos.

Parameter	Favorable		Unfavorable	
	Aerial	Terrestrial	Aerial	Terrestrial
Application time (h)	10:10 a.m.	11:00 a.m.	12:05 p.m.	11:45 a.m.
Temperature (°C)	28.6	27.0	30.5	30.3
Relative humidity (%)	61.1	62.0	52.5	53.8
Wind speed (km h^{-1})	6.5	8.9	11.1	11.7

Aerial spraying was performed with a Cessna aircraft, Ag Truck model, with a capacity of 810 kg, equipped with Full Cone Hollow Core D6 Orifice 56 nozzles, set to provide a "Very Fine" droplet spectrum. Spray volume was 20 L ha^{-1}, at 26 Psi, with a travel speed of 187 km h^{-1} and flight height of 3 m. These parameters were determined by regional frequent use. Terrestrial spraying was performed using a self-propelled Montana Parruda sprayer, model MA2527, equipped with a Flat Fan Jet ST 03 nozzle, set to provide a "Large" droplet spectrum. Spray volume was 80 L ha^{-1}, and working pressure was 55 Psi, with travel speed of 20 km h^{-1} and a spray bar height of 0.50 m. These criteria were based on recommendations for each system for the lowest drift risk without compromising target coverage efficiency. Reservoirs of both spraying equipment contained only water. Regardless of the application system, applications were always perpendicular to wind direction.

Drift potential was estimated through hydro-sensitive papers attached to a wooden support at 45° angle relative to the wooden support. The 26 x 76 mm hydro-sensitive paper spray cards were purchased in TeeJet Technologies® (São Paulo, Brazil). The wooden supports were positioned equidistantly every 20 m, using the last external tip of the spraying bar as a reference, always perpendicularly to the application and in line with wind direction. Wooden supports positioned at the same distance from the spraying bar were placed every 10 m, totaling 100 meters (considering the 10 repetitions). Thus, the distance covered for each treatment was 100 m. Figure 1 illustrates the wooden supports distribution. Wooden supports were positioned at a maximum distance of 200 meters from the first wooden support.

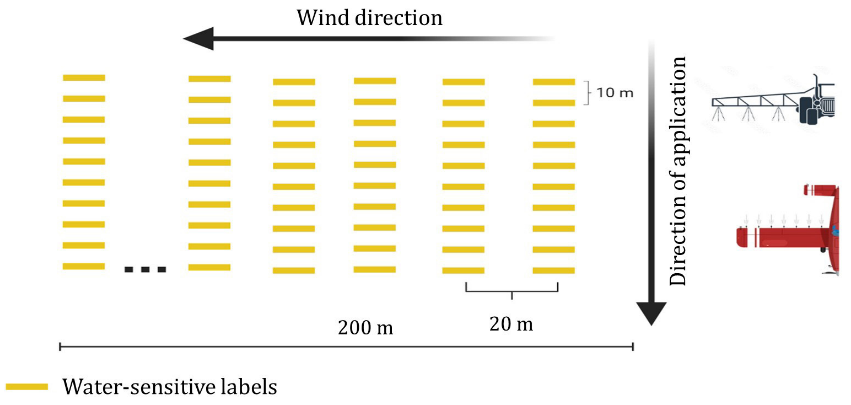


Figure 1. Scheme of the arrangement of water-sensitive papers in the experimental area.

Figura 1. Representación gráfica de la disposición de los papeles sensibles al agua en el área experimental.

After the spraying, the hydro-sensitive papers were removed and placed in a paper envelope for subsequent scanning using the CIR 1.5 software (13), at 600 dpi. After scanning, the parameters volumetric median diameter (VMD), droplet density (DEN) (drops cm^{-2}), and coverage percentage were obtained for each experimental unit.

Statistical analyses were performed using SISVAR software (7). After checking ANOVA assumptions, the F-test, was performed. When assumptions were not met, data were transformed using the Box-Cox criterion, followed by ANOVA and Tukey's test (p-value < 0.05).

Results

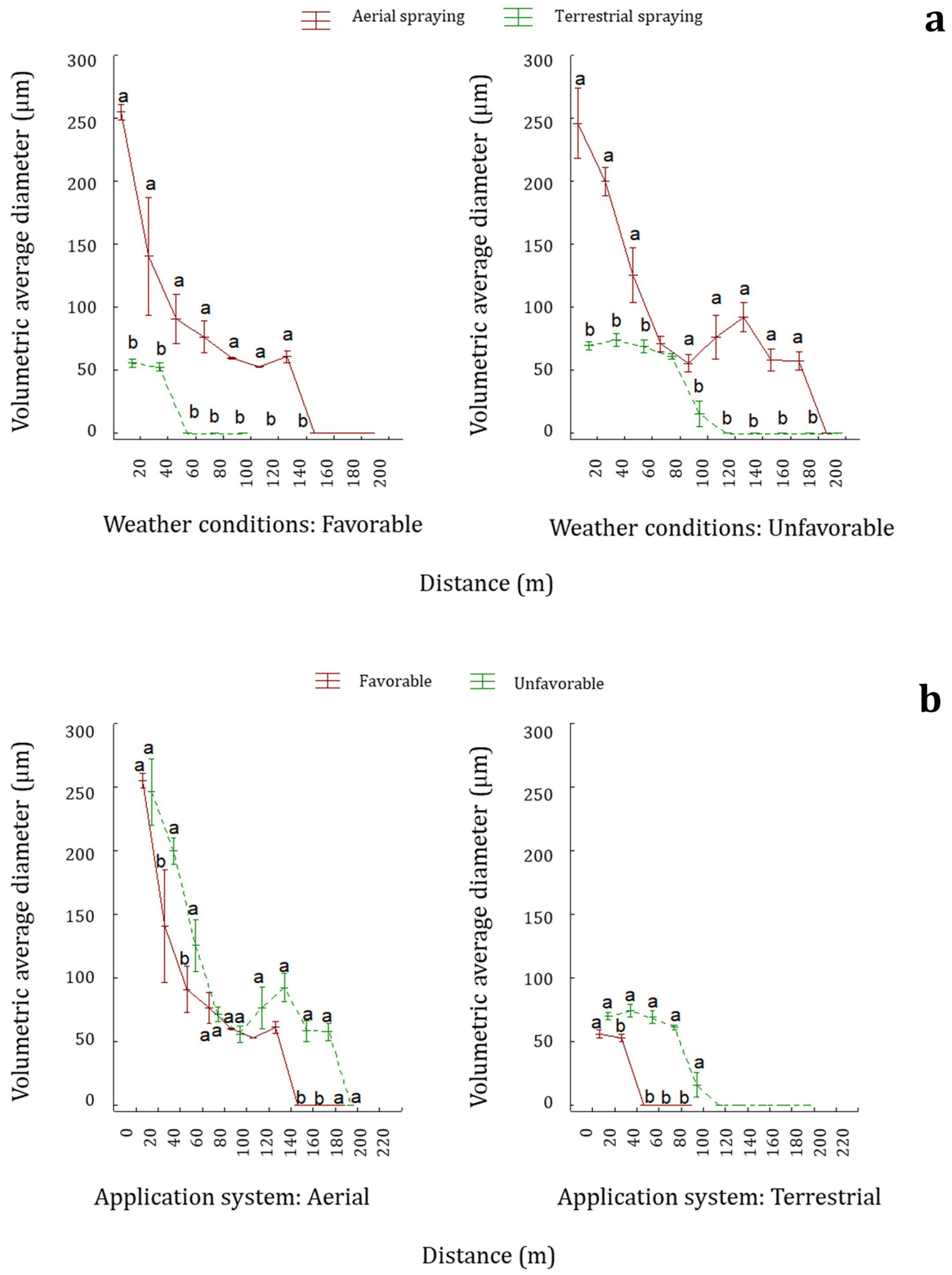
The ANOVA results for *Spray Systems* vs. *Environmental Conditions* are presented in Supplementary Material S1. The Volumetric Median Diameter (VMD) showed a significant interaction effect for either *Spray Systems* or *Environmental Conditions*, with distances exceeding 140 m.

Figure 2 (page XXX), shows differences in VMD between spraying systems under *Favorable* and *Unfavorable Conditions*. Under *Favorable* conditions, the aerial application system provided a higher VMD (ranging from 54 to 250 μm) compared to the ground-based system (ranging from 78 to 25 μm) for distances from 20 to 140 m. Beyond 140 m, no droplets were detected in either spraying system under *Favorable* conditions. Droplets were detected only up to 40 m for the ground-based spraying system. In aerial application, 74 μm VMD droplets were detected up to 140 m. Under *Unfavorable* conditions, the behavior between spraying systems for VMD was similar to *Favorable* conditions for most distances, with higher VMD values for the aerial system. Similarity in VMD between systems was only observed at 80 m.

The VMD was higher for the *Unfavorable* condition and aerial spraying at 40, 60, 100, 120, 140, 160, and 180 m (figure 2b, page XXX). The maximum distance at which droplets were detected for *Favorable* and *Unfavorable* aerial applications was 120 m (74 μm) and 180 m (77 μm), respectively. In the terrestrial spraying, the *Unfavorable* condition also resulted in a higher VMD, reaching a maximum distance of 100 m (25 μm) and 40 m (51 μm), respectively. These results demonstrate that environmental conditions at application will influence drift potential, with greater risk under *Unfavorable* weather conditions.

Under *Favorable* conditions, aerial application resulted in a higher droplet density on non-target areas, compared to terrestrial spraying. Droplet density values ranged from 2 to 23 drops cm^{-2} for aerial application and 1 to 9 drops cm^{-2} for terrestrial spraying (figure 3a, page XXX). Under *Unfavorable* conditions, terrestrial spraying provided a higher droplet density than aerial spraying at 20, 40, and 80 m. Beyond 80 m, aerial spraying promoted higher droplet density, while terrestrial spraying had null density. Different droplet density between climatic conditions in aerial spraying was only observed at 80 m (figure 3b, page XXX). Climatic conditions strongly impacted terrestrial spraying with higher droplet density under *Unfavorable* conditions compared to *Favorable* conditions and from 20 to 100 m.

Target coverage values were below 1% for all spraying systems and environmental conditions, (figure 4a and 4b, page XXX). Aerial spraying provided higher coverage than terrestrial spraying, for *Favorable* and *Unfavorable* conditions (figure 4a, page XXX). Beyond 80 m, aerial coverage was below 0.1%, regardless of climatic conditions. In terrestrial spraying, coverage below 0.1% occurred at 40 m from the target.

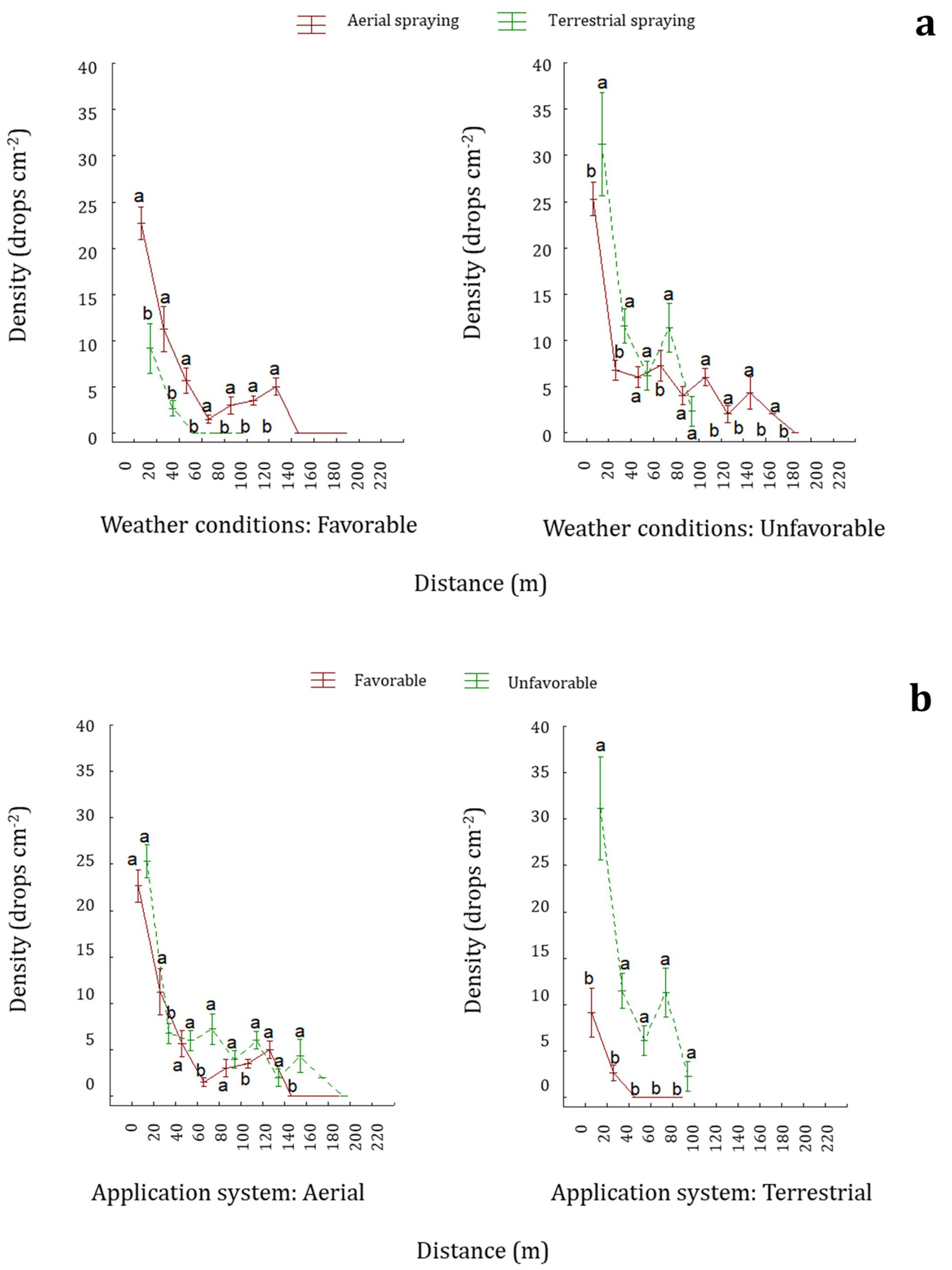


Lowercase letters show statistical differences.

Las letras minúsculas muestran diferencias estadísticas.

Figure 2. Volumetric mean diameter (μm) obtained by applications in **a**: two environmental conditions (favorable and unfavorable) from **b**: aerial and terrestrial application systems, over 200 meters considering perpendicular drift.

Figura 2. Diámetro volumétrico medio (μm) obtenido por aplicaciones en **a**: dos condiciones ambientales (favorable y desfavorable) y **b**: del sistema de aplicación aérea y terrestre en una distancia de 200 metros considerando un movimiento perpendicular de la deriva.



Lowercase letters in figure 3a differentiate application systems at each distance for each condition. Lowercase letters in figure 3b differentiate application conditions at each distance for both application system.

Las letras minúsculas en la figura 3a diferencian los sistemas de aplicación en cada distancia evaluados para cada condición de aplicación. Las letras minúsculas en la figura 3b diferencian las condiciones de aplicación en cada distancia evaluada para cada sistema de aplicación.

Figure 3. Density (drops cm^{-2}) in two environmental conditions (favorable and unfavorable) from aerial and terrestrial application systems over 200 meters considering perpendicular drift in relation to the application.

Figura 3. Densidad (gotas cm^{-2}) obtenida por aplicaciones en dos condiciones ambientales (*favorable* y *desfavorable*) del sistema de aplicación aérea y terrestre en una distancia de 200 metros considerando un movimiento perpendicular de la deriva con relación a la dirección de aplicación.

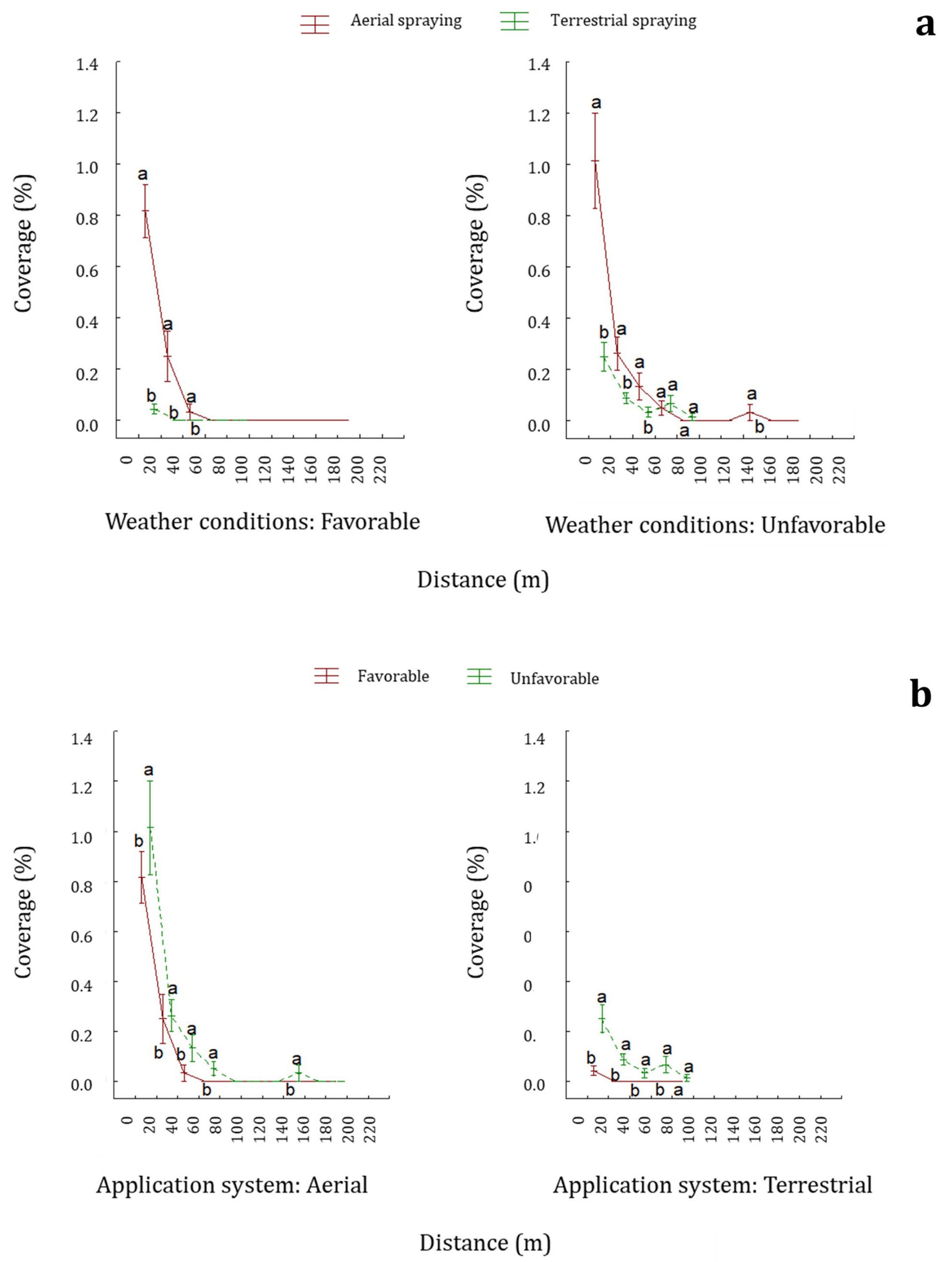


Figure 4. Coverage (%) obtained by applications in two environmental conditions (favorable and unfavorable) from the aerial and terrestrial application system over a distance of 200 meters considering a perpendicular movement of the drift concerning the direction of application.

Figura 4. Cobertura (%) obtenida por aplicaciones en dos condiciones ambientales (favorable y desfavorable) del sistema de aplicación aérea y terrestre en una distancia de 200 metros considerando un movimiento perpendicular de la deriva con relación a la dirección de aplicación.

Lowercase letters in figure 4a differentiate the application systems at each distance evaluated for each application condition. Lowercase letters in figure 4b differentiate the application conditions at each distance evaluated for each application system.

Las letras minúsculas en la figura 4a diferencian los sistemas de aplicación en cada distancia evaluados para cada condición de aplicación. Las letras minúsculas en la figura 4b diferencian las condiciones de aplicación en cada distancia evaluada para cada sistema de aplicación.

The maximum drift distance detected for ground application was 40 m and 90 m for *Favorable* and *Unfavorable* conditions, respectively (table 2). For aerial application, maximum drift values were 140 m and 180 m for *Favorable* and *Unfavorable* conditions, respectively.

Table 2. Maximum drift distance and increase thereof depending on applications carried out in different modes and climatic conditions.

Tabla 2. Distancia máxima de deriva y aumento de la misma en función de aplicaciones realizadas en diferentes modos y condiciones climáticas.

Application system	Distance (m)		Increase [1/]	
	Favorable	Unfavorable	--- % ---	--- m ---
Aerial	140	180	28	40
Terrestrial	40	90	125	50

Application system	Target coverage (%) [2/]	
	Favorable	*Unfavorable*
Aerial	25	18
Terrestrial	31	23

[1/] Increase in drift when comparing applications under ideal and adverse weather conditions. [2/] Target coverage provided on hydro-sensitive papers positioned across the application swath.

[1/] Aumento de la deriva al comparar aplicaciones en condiciones climáticas ideales y adversas. [2/] Cobertura objetivo proporcionada en papeles hidrosensibles colocados a lo largo de la franja de aplicación.

DISCUSSION

Aerial spraying showed higher drift potential in both *Favorable* and *Unfavorable* conditions. Even terrestrial application had larger VMD (coarse droplets) than aerial spraying (fine droplets), it did not reach greater distances outside the target. The shorter distance to the target and the lower traveling speed reduced lateral movement of larger droplets, allowing only lateral movement of droplets with VMD under 50 μm in *Favorable* conditions and 75 μm for *Unfavorable* conditions. Droplets of this caliber are more susceptible to wind drag, even under ideal climatic conditions.

Even though aerial spraying produced a spectrum of finer droplets, the higher target distance, travel speed, and turbulence propelled larger droplets farther from the application point. Probably, the smaller droplets of the aerial system evaporated before reaching the hydro-sensitive papers. On the other hand, larger droplets have a longer lifetime (2, 21) and were transported by the wind to distances exceeding 120 m under *Favorable* conditions and 180 m under *Unfavorable* conditions. Droplets with VMD greater than 100 μm are less susceptible to wind transport. However, for aerial spraying, 125 μm drops deposition was up to 60 m from the target under *Unfavorable* conditions. Under *Favorable* conditions, drops with VMD greater than 100 μm were transported up to 40 m given wind speed. According to Baio *et al.* (2019), wind is the most influential factor in pesticide drift for aerial spraying.

The higher droplet density observed for terrestrial spraying under *Unfavorable* conditions at 20, 40, and 80 m was given by smaller droplets traveling longer distances. For up to 80 m from the target, the higher wind speed under *Unfavorable* conditions was the prime factor modulating droplet movement. However, the lower position of the application bar compared to aerial spraying minimized drift potential with drops recorded only up to 80 m. Several studies directly correlate target distance with drift potential (12, 17, 18). In addition, aerial spraying occurred at 3 m from the target (3 m) while terrestrial spraying was at 0.5 m, increasing average time for droplets to reach the target. Probably, these droplets evaporated under *Unfavorable* conditions, failing to reach water-sensitive papers after the target. Under *Favorable* conditions, aerial spraying showed smaller droplets reaching the water-sensitive papers with higher droplet density than terrestrial spraying.

Even though drift occurred at 90 and 180 m for terrestrial and aerial spraying, respectively, under *Unfavorable* conditions, the amount of active ingredient hypothetically reaching non-target areas, is low.

Coverage was less than 0.1% for both spraying systems under this condition, proportionally low when considering target average coverage of aerial and terrestrial spraying of 18% and 23%, respectively (table 2, page XXX). The hypothetical dose reaching above 90 m would be 0.5% and 0.4% of the recommended dose for aerial and terrestrial spraying, respectively. However, some non-target organisms do not tolerate infinitesimally small doses of certain pesticides, such as dicotyledonous plants (3) or crayfish (24).

In general, higher temperature, lower relative humidity, and increased wind speed during both aerial and terrestrial spraying increased drift potential, with 28% and 125% for perpendicular and parallel distances to wind direction. Despite higher drift risk of aerial spraying, terrestrial spraying is strongly affected by environmental conditions. Under *Unfavorable* conditions, drift reached 90 m, exceeding the minimum 50 m distance established by Brazilian Law 19.423/2016 for areas with isolated dwellings and groups of animals. Considering other restrictions determined by Brazilian Law 19.423/2016, even under non-ideal conditions, terrestrial spraying proved safe. Under *Favorable conditions,* aerial spraying had a low drift risk, with maximum drift detected at 140 m, under the 250 m limit established by law.

CONCLUSIONS

The results indicate that pesticide drift in large crops is significantly influenced by spraying systems and environmental conditions. Aerial spraying shows a higher drift potential, reaching over 180 m, while terrestrial spraying under unfavorable conditions is limited to 90 m. System choice should consider droplet size and specific environmental conditions. Despite drift potential, coverage in non-target areas was under 0.1% for both systems. We highlight the importance of rigorous safety laws to minimize contamination, contributing to safer and more efficient agricultural practices.

SUPPLEMMENTARY MATERIAL

https://docs.google.com/document/d/1Clve2FAJgRYvPtRptjLEMh37Kj_OKtxs/edit?usp=sharing&ouid=111310786017351827239&rtpof=true&sd=true

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Acknowledgements

To the Rural Union of Rio Verde (Sindicato Rural de Rio Verde) for providing all the necessary infrastructure to carry out the experiment.

The Universidade de Rio Verde (UniRV) for providing financial resources to cover the costs of the analyses.