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An agroecological assessment of uncrewed aerial vehicle spraying in Greek viticulture

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ABSTRACT

Spraying pesticides with uncrewed aerial vehicles (UAVs) in European viticulture is currently only allowed when there are no viable alternatives or if it provides environmental and human health benefits. Using Greece as a case study, this analysis investigated the agroecological performance of UAV spraying in comparison with land-based pesticide application. A multi-objective linear programming model assessed farmer preferences for spraying pesticides with ground equipment or a UAV. Farmers concerned with non-economic goals preferred UAV targeted pesticide application, while production-orientated farmers favoured ground spraying. Depending on disease pressure, UAV spraying generated annual savings of €278–377 ha^{-1} on a flat vineyard compared to a trailed vine sprayer and €367–538 ha^{-1} on a steep-slope vineyard compared to a backpack sprayer. However, the estimated costs of custom-hiring UAVs in Greece made UAV spraying less profitable except in conditions of simultaneous extreme labour scarcity and high disease pressure on the steep-slope vineyard. UAV aerial broadcast had an environmental impact comparable to ground spraying, but UAV spot-spraying mitigated ecotoxicological risks of pesticide use by 46–50 %. Both UAV spraying methods substantially reduced human exposure to pesticides. In current regulation, UAV aerial broadcast would only be allowed in steep-slope viticulture if seasonal labour was unavailable. UAV spot-spraying could be permitted on both vineyards, but it would be economically feasible if hiring fees were €43–49 ha^{-1}. The study concludes with recommendations to promote UAV spraying adoption among European farmers thereby contributing to the EU objectives to halve pesticide use and risk while potentially resolving labour availability challenges on abandonment-prone vineyards.

1. Introduction

In Europe, viticulture is not only a valuable segment of the rural economy, but also provides important ecosystem services and constitutes rich cultural heritage [1]. Today, the sector is challenged by farm management factors such as pesticide resistance, labour scarcity, and increasing production costs as well as external factors including declining wine consumption and climate change [1,2]. These have led to vineyard abandonment across multiple European regions, especially on steep-slope vineyards [3–6]. The adoption of precision viticulture technology such as uncrewed aerial systems (UASs) is expected to mitigate some of these challenges by maintaining or possibly increasing profitability while reducing environmental impact, promoting resilience to external shocks and enhancing farm workers' safety [5,8–11]. UASs include three components: an uncrewed aerial vehicle (UAV), a land-based controller, and a communications system [11]. They were initially developed for military purposes and first applied in the agricultural domain mainly as a remote sensing tool [8,9,11–13]. For example, agricultural drones have been used to collect farm data related to soil characteristics, nutrient stress level, crop stand count, and presence of invasive weeds, insects and diseases [9,11–13]. In recent years, the use of UAVs for aerial spraying of fertilisers and pesticides has also grown rapidly worldwide [5,9,14].

UAV spraying technology is constantly evolving towards higher payloads, faster flowrates and speeds, longer battery duration and enhanced data processing [15]. The latest UAV models are able to carry up to 75 l of agricultural inputs, deliver flowrates of up to 30 l min^{-1}, achieve speeds of 14 m s^{-1}, and fly for up to 20 min per battery recharge while relying on precise 3D route planning and 360-degree obstacle detection and avoidance software [16,17]. Spray drones are a niche

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market in several countries including Australia, China, Switzerland and the US [18,19,20,21]. UAVs are advantageous in wet soil conditions, small and irregularly shaped fields, unfavourable topography, and for operations conducted after broadacre crop establishment to avoid plant damage [5,13]. By exploiting UAV imagery in spraying operations, precision application of agricultural inputs becomes possible thanks to high resolution images collected at low altitudes without interference by cloud cover [15]. This technique, known as spot- or patch-spraying, has the potential to reduce the impact of pesticide use on the environment [12,22]. Applying agricultural inputs with a drone can also reduce exposure of farm operators, especially for those using hose or backpack sprayers [5,10,13,23]. Because of these benefits, analysts expect that the agricultural drone market will grow by 20 % per year between 2023 and 2030, reaching a value of over US$18 billion by the end of this period and becoming the second largest user of drones in the world [13,24]. However, EU farmers and farm contractors are unable to exploit this opportunity due to regulation banning most aerial spraying in the continent. This is despite the potential of UAVs for helping to meet the EU objective to halve pesticide use and risk established in the European Green Deal and the EU Biodiversity Strategy for 2030 [25,26].

UAV spraying may potentially generate increased risks related to interference with airspace, privacy breaches, pesticide spray drift, and pest resistance caused by insufficient or uneven droplet deposition [8, 14,24]. Consequently, regulation of spray drones in the EU is complex and their manufacturing requirements and operational use are the responsibility of multiple authorities. Based on Regulation (EU) 2019/947, spray drones fall in the certified UAV category because they carry pesticides, which are considered as dangerous goods by Art. 6 [27]. Operating a spray drone in agriculture is governed by Directive 2009/128/EC, which generally prohibits aerial spraying [28]. However, Art. 9 of Directive 2009/128/EC grants derogations if there are no viable alternatives to ground spraying (e.g., on difficult terrain) or there is an advantage “in terms of reduced impacts on human health and the environment compared with land-based application of pesticides” [28: Art. 9(2)]. In some Member States, exceptional permissions for using spray drones have been granted in recent years. For example, UAV spraying has been allowed in Germany to apply fungicides on steep-slope vineyards [29] and in Hungary to spray a neonicotinoid insecticide on cherries and walnuts [30]. Nevertheless, these permissions are costly, time-consuming and are released on a crop-by-crop and chemical-by-chemical basis, thereby limiting large-scale adoption of UAV spraying in the EU. Additionally, Directive 2009/128/EC mandates that drone operators must only use UAVs equipped with “best available technology to reduce spray drift” [28: Art. 9(2)], which may limit pesticide efficacy and promote resistance development for certain crops and active substances [14,31].

Although spray drones have attracted increasing attention in the literature over the last decade [8,9], the economic feasibility of this technology has rarely been studied [32]. Because one of the prerequisites for spray drone use in EU agriculture is to provide environmental and human health benefits, this research used a multi-criteria assessment to simultaneously investigate the economic, environmental and social implications of existing UAV spraying regulation in Europe. Greek viticulture was chosen as case study due to its economic importance and vineyard management characteristics. With over 64,000 ha allocated to winegrapes, Greek wine production represents 2 % and 1 % of total European and global production, respectively [33]. Mean vineyard size is relatively small (3.9 ha), which poses structural challenges for the economic feasibility of the sector [4,34]. This also leads to Greek vineyards being mainly managed by owners and family members [35, 36], who tend to be involved with off-farm employment and neglect continuation of farming [35]. Consequently, Greece has experienced severe agricultural land abandonment, including a substantial discontinuation of permanent crops [4]. Key factors triggering this phenomenon have been a challenging topography in regions like Crete where steep-slope agriculture is common, as well as economic factors such as low income and high indebtedness making it difficult for Greek farms to adapt to new technologies [4,37]. The latter aspect is of particular importance in viticulture considering the high labour inputs required to manage vineyards lacking mechanisation, especially for operations such as winter pruning, harvesting and pesticide application [38]. In this context, custom-hired UAV spraying could play an important role by reducing labour inputs and improving vineyard profitability, while providing an opportunity to reduce the impact of pesticide use on the environment and human health and to spur continuing cultivation of Greek vineyards.

To enable a more comprehensive analysis, this study simulated UAV spraying on two vineyard types characterised by a different degree of slope. A highly mechanised flat vineyard was modelled to investigate the competitiveness of custom-hired UAV spraying where labour efficient and relatively cheap pesticide application approaches have long been adopted. On the other hand, the analysis of UAV spraying on steep-slope vineyards was intended as an example where the alternative spraying strategy is as labour intensive as backpack spraying, which may not always be a viable alternative especially in situations of extreme labour scarcity. A range of farm management factors such as decision-maker utility, economic return, environmental impact, and operators’ risk of exposure to pesticides were quantified. This multi-criteria assessment built on an initial study by Maritan et al. [39] by expanding the range of modelled scenarios to include conditions of high disease pressure requiring ground pesticide application complimentary to aerial spraying. Scenarios relying on UAV spot-spraying to reduce the environmental impact of pesticide use were also added. Spray drone operational parameters were devised to be reasonably likely to obtain derogation under Directive 2009/128/EC. Spray drift risk was mitigated by selecting a drone model capable of producing coarse droplets and by abiding with weather parameters following ISO 23117–1:2023 [40]. The hypotheses of this study were that: (i) UAV spraying is presently less profitable than conventional ground spraying; (ii) the environmental impact of UAV spraying with current technology can only be reduced via targeted pesticide application; and (iii) the risk of human exposure to pesticides is lower when using UAVs compared to conventional ground equipment.

2. Materials and methods

2.1. Hands free hectare multi-objective linear programming (HFH-MOLP) model

The HFH-MOLP model is a decision-making support tool capable of estimating farmer utility in situations of conflicting economic, ecological and social objectives based on the deviation from a set of farm-level targets [41]. This model was developed as part of the Digitalisation for Agroecology project [42] to provide representative comparisons of conventional and innovative agricultural technologies concerned with their potential for enabling agroecological farming in Europe. The HFH-MOLP model uses the goal programming approach described in Hazell and Norton [43: p.72]. It is an extension of the Hands Free Hectare linear programming model developed by Preckel et al. [44] and adapted by Lowenberg-DeBoer et al. [45]. This analysis used the HFH-MOLP model to estimate three farm-level goals for three decision-maker types motivated by different priorities. The model was run in the General Algebraic Modelling System software [46]. The HFH-MOLP model code is available in **Appendix A** in the supplementary materials included in the online version of this article.

The goals assessed in this study were farm gross return, environmental impact and human exposure to pesticides. These goals were used to quantify the degree to which hypothetical decision-makers satisfied a pre-determined set of objectives when adopting a whole-farm plan optimised for the range of available farm resources. The underlying assumption was that adoption of agroecologically desirable practices would only be possible with an increase in overall farmer utility compared to conventional practice [7]. The model used the following objective function:

$$\min G = w_1\left(\frac{G_1^-}{G_{opt}^1}\right) + w_2\left(1 - \frac{G_2^-}{G_{wrs}^2}\right) + w_3\left(1 - \frac{G_3^-}{G_{wrs}^3}\right) \tag{1}$$

where G was the target variable to be minimised, representing the loss of farmer utility incurred when objectives were not fully satisfied; w_1, w_2 and w_3 were weights respectively assigned to the economic, ecological and social objectives to reflect farmer priorities; G_1^-, G_2^- and G_3^- were variables quantifying the negative deviation from desired or undesired goals; and G_{opt}^1, G_{wrs}^2 and G_{wrs}^3 were the desired or undesired goals used to normalise objective achievement.

This equation indicates that farmers aimed to maximise farm gross return (i.e., the desired goal) while minimising environmental impact and human exposure to pesticides (i.e., the undesired goals). If these goals were fully satisfied, the model would assign a value of zero to G, corresponding to a maximum level of satisfaction (100 %). The ecological and social objectives were removed from the above equation by setting w_2 and w_3 equal to zero to represent decision-makers whose priorities were not related to the ecological and/or social domain. The three modelled decision-makers were a production-orientated farmer ($w_1 = 100$ %, $w_2 = w_3 = 0$ %), an ecologically-orientated farmer ($w_1 = 70$ %, $w_2 = 30$ %, $w_3 = 0$ %), and a socially-orientated farmer ($w_1 = 70$ %, $w_2 = 0$ %, $w_3 = 30$ %). The production-orientated farmer only prioritised farm gross return and would not be concerned with reducing the impact of pesticide use on the environment and human health even if these were mandated by regulation. In farmer behaviour literature, this decision-maker typology has for example been referred to as productivist farmer [47] or yield optimiser [48]. For the ecologically- and socially-orientated farmers, a weight of 30 % was considered as a reasonable value to represent non-economic priorities while ensuring the necessary economic viability for farm business survival [7,49]. The ecologically-orientated farmer was assumed to gain a higher satisfaction when managing an economically feasible enterprise while minimising the impact of pesticide use on the environment. In farmer behaviour literature, this farmer typology has for example been labelled as ecologist [50] and environmentalist farmer [47]. Lastly, the socially-orientated farmer was considered as a farmer typology prioritising aspects such as workers' safety and well-being. In this analysis, these elements were associated with risk of human exposure to pesticides, but farmer types motivated by other social aspects may fall in this category such as the part-time and social farmers described by Schmitzberger et al. [48] or the traditionalist farmer defined by Bartkowski et al. [47]. Because they appear to be uncommon in Europe, farmers simultaneously prioritising ecological and social objectives were not included in this study [47].

2.2. Model objectives

The economic objective was measured as farm gross return. This was calculated by deducting variable costs from the sum of sales revenue and EU Common Agricultural Policy (CAP) payments. Variable costs included fertilisers, pesticides, fuel, wages for temporary workers, UAV hiring fees and cost of a custom-hired winegrape harvester when harvesting was not manual. Variable costs are available in **Supplementary Table S1**. Winegrape prices and yields were respectively €720 tonne^{-1} and 9.7 tonnes ha^{-1} based on average values for the 2013–2022 period [51,52]. Based on expert advice, a yield loss of 10 % was deducted when the model was unable to apply pesticides at the optimal time. CAP payments included the basic income support for sustainability (€270 ha^{-1}) on both vineyards plus the complementary redistributive income support (€116 ha^{-1}) and a payment for mountainous areas (€119 ha^{-1}) on the steep-slope vineyard [53,54,55].

Gross return excluded farm operator labour, management, risk taking and fixed costs. Farm operator labour and management were excluded because the two modelled vineyards were assumed to be family-run and family labour is generally compensated out of profits in small farm businesses [56]. Risk was modelled using the good field days approach described in Lowenberg-DeBoer et al. [45] whereby farm operations could only occur if favourable weather conditions were sufficiently likely to be satisfied in any given year. Weather data for Attica and Crete were extracted from an online database [i.e., 57]. For ground equipment, good field days were estimated based on the mean number of days without rain available in eight years out of ten (i.e., 80 % of the cases). For UAV spraying, good field days also accounted for the weather requirements described in ISO 23117–1:2023, which included a temperature between 10 °C and 35 °C, a relative humidity below 70 % and a maximum wind speed of 2.0 m s^{-1} [40]. Monthly good field days for ground and aerial equipment are provided in **Supplementary Table S2**. Fixed costs were not accounted for in estimating gross return but subtracted after running the model to analyse vineyard long-term profitability based on the Return to Operator Labour, Management and Risk Taking (ROLMRT) indicator. Fixed costs included vineyard installation, maintenance and insurance, annual machinery costs, and opportunity cost of land. Vineyard installation and maintenance and annual machinery costs were quantified based on data from Italy and Romania (see **Supplementary Table S3**) while the vineyard insurance premium was obtained from the Hellenic Agricultural Insurance Organisation online portal [58]. In the absence of vineyard land ownership and tenancy data for Greek viticulture, opportunity cost of land was calculated based on regional market land rental rates provided by EUROSTAT [59]. Lastly, winegrape production costs were estimated to assess the competitiveness of vineyards adopting UAV spraying compared with non-adopters. Winegrape production costs accounted for variable and fixed costs as well as opportunity cost of family labour. The latter was quantified based on the €830 month^{-1} minimum salary for employees in Greece [60] plus an additional 20 % as compensation for marketing and management following Lowenberg-DeBoer et al. [45].

The two non-economic objectives were measured through the Pesticide Load Indicator (PLI) methodology developed by the Danish Environmental Protection Agency [61] and used to appraise pesticide tax in Denmark [62]. More details on the PLI can be found in Kudsk et al. [62] and Lewis et al. [63]. To fit in the HFH-MOLP model, the PLI methodology was broken down into four unitless indicators corresponding to specific model goals and sub-goals. Higher indicator scores corresponded to a greater impact on the environmental or social aspect under consideration. The ecological objective was expressed as the mean of three undesired sub-goals, namely: biodiversity loss, soil health reduction and water pollution. A range of parameters by active substance was extracted from the pesticide properties database maintained by the University of Hertfordshire [64]. Biodiversity loss was set equal to the mean of pesticides bio-concentration risk in off-target species and the pesticide load for ecotoxicology (PL_{eco}). The latter accounted for mortality risks of acute and chronic active substance exposure for a range of terrestrial and aquatic indicator species [62]. Soil health reduction corresponded to risk of pesticides persistence in soil using active substance half-life values (i.e., DT_{50}). Water pollution was calculated as the mean of pesticide surface and groundwater mobilities, respectively based on Freundlich soil-water partition coefficients (i.e., k_{foc}) and groundwater ubiquity scores. To enable comparison over time, all these indicators must be estimated in relation to a reference value coinciding with the most harmful active substance for a specific indicator [62]. This reference value depends on the list of active substances available in the country at the time of PLI adoption. Because the PLI approach has not been adopted in Greece, this analysis used Danish active substance reference values. Although the estimated environmental impact indicators may be only a rough estimate for Greece, this approach provided a relative indicator across pesticide spraying strategies.

Lastly, the pesticide load for human health (PL_{hh}) was isolated to quantify a human exposure to pesticides goal representing the social objective in the HFH-MOLP model. The PL_{hh} is based on a scoring system of the risk phrases present on pesticide labels multiplied by an exposure factor which depends on the form of the plant protection product (PPP) considered [62]. If the PPP is in powder or liquid form, the resulting score must be multiplied by 1.5 to account for an increased risk of exposure during pesticide mixing and loading compared to solid formulations [62]. The original PLI methodology did not account for modified risks of operators' exposure that are dependent on spray equipment type. Thus, following findings by Kuster et al. [10], exposure factors of 0.5 and 1.5 were multiplied by the exposure factors for pesticide form when spraying pesticides with a UAV and a backpack sprayer, respectively. Additionally, farm operators were assumed to wear protective clothing and to use a closed tank transfer system to limit interaction with the pesticide mix during the frequent refills required when using a spray drone or a backpack sprayer [10].

2.3. Scenarios

Model goals were estimated for 12 scenarios combining two vineyard types, two disease pressure levels and three pesticide spraying strategies (Table 1). The first vineyard type was a flat vineyard located in Attica, the most commercially important viticultural region of Central Greece [37]. The vineyard had an area of 8 hectares and hosted 66 vine rows with vines spaced at 2.2 × 1.2 m. The second vineyard was located in Crete, where the majority of viticulture takes place on steep-slope vineyards [37]. This vineyard had an area of 3 hectares and hosted 39 vine rows with vines spaced at 2.2 × 1.2 m. Vineyard areas corresponded to mean vineyard sizes in the two target regions based on data published by the Hellenic Statistical Authority (ELSTAT) [34]. Both vineyards produced a mixture of white and red varieties for direct sale (i.e., no winemaking). Vines were assumed to be trained with a vertical shoot positioning system. Half of the scenarios were subjected to high fungal disease pressure requiring additional pesticide treatments.

Pesticide application included three alternative strategies: (i) conventional ground spraying, (ii) UAV aerial broadcast, and (iii) UAV spot-spraying. Pesticides available in Greece [65] were sprayed in a water mix volume of 400 l ha^{-1} regardless of equipment type to abide with product label requirements. The ground sprayers were a 600-litre vine sprayer (Caffini Smart Synthesis Hybrid, Caffini S.P.A., Verona, Italy) on the flat vineyard [66] (Fig. 1**(A)**) and a 20-litre backpack sprayer (TOTAL Knapsack Sprayer, TOTAL Tools Malaysia, Puchong, Malaysia) on the steep-slope vineyard [67] (Fig. 1**(B)**). The vine sprayer required 0.59 h ha^{-1} for a spraying pass, which was substantially faster than backpack spraying on the steep-slope vineyard. Backpack spraying time was calculated based on a pesticide output of 1 l min^{-1} and 20 refills per hectare per spray requiring 5 mins for each refill, thus totalling 8.34 h ha^{-1}. The hired UAV model was assumed to be a XAG P100 (XAG Co. Ltd., Guangzhou, PRC) because of its capacity to produce coarse droplets and a relatively high field efficiency thanks to its 40-litre spray tank [68] (Fig. 1**(C)**). Drone spraying covered three vine rows per pass (i.e., working width = 6.6 m) at a speed of 3 m s^{-1} and at a height of 2 m above the canopy. UAV speed and height parameters considered multiple literature findings to achieve appropriate droplet size and distribution while minimising spray drift [5,40,69,70]. UAV supervision was assumed to be 100 % because of visual-line-of-sight rules in the EU. UAV aerial broadcast required 0.16 h ha^{-1} on the flat vineyard and 0.17 h ha^{-1} on the steep-slope vineyard due to a lower field efficiency on smaller vineyards. UAV spot-spraying operations achieved a 50 % reduction of pesticide input by assuming that spray spots occupied half of the vine area. UAV spot-spraying times depended on the number and length of spray spots and accounted for acceleration and deceleration zones before and after active spraying to limit spray drift on non-target areas. UAV spot-spraying required 0.12 h ha^{-1} per pass on both vineyards. Following the most common operational practice at the current technological stage, UAV spot-spraying relied on prescription maps prepared by the farm operator during management time. The farm operator was assumed to walk along the vine rows with a mobile phone and select the spray spots on a vineyard map to be later uploaded to the UAV flight plan by a UAV spraying contractor.

Fig. 1. Pesticide spraying equipment used across scenarios: (A) the Caffini Smart Synthesis Hybrid vine sprayer [66,71]; (B) a backpack sprayer [67,72]; and (C) the XAG P100 spray drone [68,73].

Table 1
Outline of the 12 scenarios assessed in this study.

Vineyard type	Disease pressure	Pesticide spraying strategy	Scenario
Flat vineyard, Attica (8 ha)	Low	Vine sprayer	1L-A
		UAV aerial broadcast	1L-B
		UAV spot-spraying	1L-C
	High	Vine sprayer	1H-A
		UAV aerial broadcast + Vine sprayer	1H-B
		UAV spot-spraying + Vine sprayer	1H-C
Steep-slope vineyard, Crete (3 ha)	Low	Backpack sprayer	2L-A
		UAV aerial broadcast	2L-B
		UAV spot-spraying	2L-C
	High	Backpack sprayer	2H-A
		UAV aerial broadcast + Backpack sprayer	2H-B
		UAV spot-spraying + Backpack sprayer	2H-C

Based on the experience of steep-slope viticulture in Germany where spray drones are commonly custom-hired [74], UAV spraying was assumed to be performed by a contractor. The UAV aerial broadcast fee was estimated to be €125 ha^{-1} including labour, pesticide and setup costs. This fee was equivalent to half of the mean UAV spraying fee charged on steep-slope vineyards in Germany [74] to account for lower labour and variable costs in Greece. The UAV spot-spraying treatment assumed 50 % of pesticide use and consequently a lower fee, which was estimated at €104 ha^{-1} by deducting pesticide savings from the UAV aerial broadcast fee. These UAV hiring fees were substantially higher than fees charged in countries such as Australia, China and the US. In Australia and the US, recent consultations with spray drone service providers reported that UAV spraying costs €21 ha^{-1} in Australia (AU\$1 = €0.60) and €26–71 ha^{-1} in the US (US\$1 = €0.95) [19,75]. However, assuming similar fees in Greek viticulture would have not been credible because UAV spraying in those countries is governed by less restrictive regulation, it is often applied on large broadacre farms with consequent field efficiency and labour time benefits, and it is practised more widely [19,76,77]. In China, where UAV spraying fees are in the range of €14–29 ha^{-1}, the conditions are even less representative of Greece considering that monetary incentives are available for both UAV purchase and operation [21].

2.4. Pesticide treatment plan

This analysis focused on fungal diseases because they are the main contributors to pesticide use in viticulture [1]. The diseases considered were powdery mildew and downy mildew owing to their frequent incidence [1], substantial impact on winegrape yields (e.g., Koledenkova et al. [78]), and some availability of UAV spraying efficacy data related to these pests [5,18]. The pesticide treatment plan considered Fungicide Resistance Action Committee recommendations [79] and included four to eight sprays per year depending on disease pressure (Table 2). The same combination of fungicides was sprayed on both vineyards. UAV spraying efficacy in low disease pressure conditions was assumed to be equivalent to ground equipment spraying based on results by Dubuis and Jaquerod [18]. In the UAV scenarios characterised by high disease pressure, two of the additional four sprays were broadcast with ground equipment to ensure a degree of fungal disease control comparable to ground spraying [5,18].

2.5. Equipment and labour times

Annual vineyard operations to estimate equipment and labour times across scenarios were based on the classification described by Strub [38] and assumed a 10-hour workday. Following latest ELSTAT data on the composition of the agricultural workforce in Greece [36], both vineyards were assumed to be managed by one family member across the year with the support of two seasonal workers per month when required during peak times. Sensitivity analyses of these labour availability assumptions were also conducted to identify potential bottlenecks in situations of extreme seasonal labour scarcity i.e., when ground spraying could cease to be a viable alternative to UAV spraying.

Table 2
Pesticide treatment plan. Treatments in italic are only applicable to scenarios characterised by a high disease pressure.

Spray pass #	PPP	Active substance(s)	Rate (kg ha^{-1} or l ha^{-1})[*]
1	FOLPAN® ENERGY	Dipotassium phosphonate + Folpet	1.60
	SULFOMAT® 80 WG	Calcium polysulphide	6.00
	MILDFOS®	*Dipotassium phosphonate*	*1.00*
2	SULFOMAT® 80 WG	Calcium polysulphide	6.00
	DYNALI® 60/30 DC	Cyflufenamid + Difenoconazole	0.25
	ZORVEC VINABEL® 340 SE	Oxathiapiprolin + Zoxamide	0.50
3	DELAN® PRO 12.5/56.1 SC	Dipotassium phosphonate + Dithianon	2.50
	SERCADIS® 30 SC	Fluxapyroxad	0.30
4[**]	*DYNALI® 60/30 DC*	*Cyflufenamid + Difenoconazole*	*0.25*
	ZORVEC VINABEL® 340 SE	*Oxathiapiprolin + Zoxamide*	*0.50*
5[**]	*ENERVIN® 20 SC*	*Ametoctradin*	*1.20*
	LUNA® EXPERIENCE SC	*Fluopyram + Tebuconazole*	*0.15*
6	ARMICARB® 85 SP	Potassium hydrogen carbonate	2.00
	ORONDIS® ULTRA 3/25 SC	Mandipropamid + Oxathiapiprolin	0.67
7	*ARMICARB® 85 SP*	*Potassium hydrogen carbonate*	*2.00*
	DYNALI® 60/30 DC	*Cyflufenamid + Difenoconazole*	*0.25*
8	*TALENDO® 20EC*	*Proquinazid*	*0.80*
	COPFORCE® EXTRA	*Copper hydroxide + Cymoxanil*	*2.00*

[*] Fungicide rates were equivalent to 50 % of the indicated values when applied via UAV spot-spraying.

[**] These spray applications were assumed to be performed using ground equipment also in the UAV spraying scenarios following Poss et al. [5] and Dubuis and Jaquerod [18].

Equipment and labour times are provided in **Supplementary Table S4** and **Supplementary Table S5**, respectively. On the flat vineyard, winter pruning, most canopy management operations and winegrape harvesting were assumed to be mechanised. Conversely, these operations were manually conducted on the steep-slope vineyard owing to its topography. Manual operation times were obtained from available vineyard management literature [80,81,82], whereas labour times for mechanised operations matched corresponding machine times. The latter were calculated based on the field efficiency algorithm developed by Al Amin et al. [83]. Because labour costs were assumed to be included in the custom-hiring fees, labour times for mechanical yield regulation and mechanical harvesting were not calculated. Both these operations were conducted with a mechanised winegrape harvester. Mechanical yield regulation relied on a winegrape harvester used at a low frequency with some beater bars removed [80].

3. Results

The results of the HFH-MOLP model identified different pesticide treatment preferences for the three decision-maker types considered (Table 3). The production-orientated farmer gained a higher satisfaction when relying on ground spraying equipment on both vineyards and regardless of disease pressure level. The second-best choice was UAV spot-spraying, though the utility of UAV aerial broadcast was only 2 % lower than this pesticide application strategy. Ecologically-orientated farmers preferred hiring UAV spot-spraying on both vineyards while their second preference was ground spraying equipment. On the other hand, the socially-orientated farmer obtained the lowest utility when using ground spraying equipment. In this case, UAV spot-spraying and UAV aerial broadcast respectively ranked first and second. Satisfaction levels were always lower in high disease pressure scenarios because of higher costs and pesticide use when additional spraying passes were necessary for efficacious pest control.

Model goal results are shown in Table 4. Ground equipment scenarios were always more profitable than their aerial spraying counterparts at the estimated fee and capacity levels. Depending on fungal disease pressure, gross return was 6–9 % higher than UAV aerial broadcast and 4–6 % higher than UAV spot-spraying when using a vine sprayer on the flat vineyard. The gross return difference between ground and UAV spraying was slightly lower on the steep-slope vineyard. Profits declined by 5–7 % and 3–5 % when hiring UAV aerial broadcast and UAV spot-spraying, respectively. Additionally, on the steep-slope vineyard, UAV spraying saved 12 to 15 farm operator days per year regardless of disease pressure plus 4 seasonal labour days in high disease pressure conditions. The reduced reliance on seasonal labour on this vineyard generated savings of €44 ha^{-1} yr^{-1}. €167 ha^{-1} yr^{-1} and €250 ha^{-1} yr^{-1} were also saved in low and high disease pressure scenarios due to reduced fungicide costs on both vineyards when hiring a spray drone. On the flat vineyard, an additional cost reduction of €5 ha^{-1} yr^{-1} and €7

Table 3
Decision-maker utilities by scenario.

Scenario	Production-orientated farmer	Ecologically-orientated farmer	Socially-orientated farmer
1L-A	100 %	81 %	84 %
1L-B	94 %	77 %	88 %
1L-C	96 %	88 %	93 %
1H-A	97 %	68 %	68 %
1H-B	89 %	62 %	77 %
1H-C	91 %	78 %	86 %
2L-A	100 %	81 %	84 %
2L-B	95 %	78 %	91 %
2L-C	97 %	88 %	95 %
2H-A	97 %	68 %	68 %
2H-B	91 %	64 %	83 %
2H-C	93 %	79 %	89 %

Table 4
Annual gross return, biodiversity loss, soil health reduction, water pollution, and exposure to pesticides by scenario. Environmental and social goals are expressed as unitless indicators representing the level of impact of pesticide use on the environment and human health. Higher indicator values correspond to greater impacts.

Scenario	Gross return	Biodiversity loss	Soil health reduction	Water pollution	Exposure to pesticides
1L-A	€ 49,718	6.89	572.36	98.21	34.98
1L-B	€ 46,946	6.89	572.36	98.21	17.49
1L-C	€ 47,648	3.45	286.39	49.14	8.75
1H-A	€ 48,276	11.66	591.04	294.92	66.32
1H-B	€ 44,117	11.66	591.04	294.92	33.95
1H-C	€ 45,170	6.14	299.20	160.00	17.59
2L-A	€ 21,226	2.40	199.61	34.25	18.30
2L-B	€ 20,246	2.40	199.61	34.25	6.10
2L-C	€ 20,490	1.20	99.91	17.14	3.05
2H-A	€ 20,605	4.07	206.13	102.85	33.92
2H-B	€ 19,266	4.07	206.13	102.85	11.68
2H-C	€ 19,633	2.14	104.38	55.81	6.29

ha^{-1} yr^{-1} resulted from fuel savings respectively in low and high disease pressure conditions. The total variable costs savings in the UAV scenarios amounted to €171–257 ha^{-1} yr^{-1} on the flat vineyard and €167–294 ha^{-1} yr^{-1} on the steep-slope vineyard. However, the estimated costs of hiring a UAV exceeded these savings in all aerial spraying scenarios. The total UAV aerial broadcast hiring costs were €500 ha^{-1} yr^{-1} if disease pressure was low and €750 ha^{-1} yr^{-1} if disease pressure was high. The correspondent values for UAV spot-spraying were €417 ha^{-1} and €625 ha^{-1} per year. The fee reduction assumed for UAV spot-spraying was not sufficient to make this fungicide treatment strategy more profitable than ground spraying.

As to the non-economic objectives, UAV spot-spraying was found to be beneficial in terms of environmental impact, whereas UAV aerial broadcast produced results comparable to ground spraying. Environmental impact scores in the UAV spot-spraying scenarios were 50 % lower than ground spraying in low disease pressure conditions and 46–49 % lower in high disease pressure conditions depending on the environmental indicator considered. On the other hand, both UAV aerial broadcast and UAV spot-spraying resulted in improved farm operator safety. On the flat vineyard, human exposure to pesticides was reduced by 49–50 % when hiring UAV aerial broadcast and by 73–75 % when hiring UAV spot-spraying. On the steep-slope vineyard, operator safety benefits compared to ground spraying were even more substantial, with a 66–67 % reduction in human exposure to pesticides in the UAV aerial broadcast scenarios and 81–83 % in the UAV spot-spraying scenarios. On both vineyards, high disease pressure conditions led to UAV spraying achieving slightly lower pesticide exposure reductions because of the additional ground broadcast sprays required.

The long-term profitability of the two modelled vineyards was investigated by deducting annual fixed costs from the gross return values shown in Table 4. Annual vineyard installation, maintenance and insurance were €19,644 on the flat vineyard and €6,851 on the steep-slope vineyard. The opportunity cost of land amounted to €8,835 yr^{-1} on the former and €2,622 yr^{-1} on the latter. Machinery costs were €12,430 yr^{-1} in scenarios using a vine sprayer and €10,815 yr^{-1} in UAV scenarios characterised by a low disease pressure on the flat vineyard. On the steep-slope vineyard, these values were €6,923 yr^{-1} if the farmer owned a backpack sprayer and €6,917 yr^{-1} otherwise. ROLMRTs across scenarios were always positive, thus highlighting the economic viability of the modelled vineyards in the long term regardless of pesticide spraying strategy. However, ground spraying remained the most profitable option on both vineyards also in the long term. Indeed, the additional annual fixed costs savings of €191 ha^{-1} on the flat vineyard and of €2 ha^{-1} on the steep-slope vineyard in low disease pressure scenarios were still insufficient to compensate for the cost increase incurred when hiring a spray drone. In high disease pressure scenarios, no fixed cost savings were obtained because ground spraying equipment ownership was also needed in the UAV spraying scenarios. ROLMRT in the conventional vine sprayer scenarios was 13–56 % higher than UAV aerial broadcast and 5–42 % higher than UAV spot-spraying depending on disease pressure level. In the backpack spraying scenarios, ROLMRT differences amounted to 20–32 % in comparison to UAV aerial broadcast and 15–23 % in comparison to UAV spot-spraying. Furthermore, adoption of UAV spraying led the modelled vineyards to become more reliant on CAP payments for long-term business survival. In the ground equipment scenarios, CAP payments represented 26–31 % and 31–35 % of ROLMRT on the flat and steep-slope vineyard, respectively. Conversely, on the flat vineyard, depending on disease pressure, CAP payments corresponded to 30–71 % of ROLMRT when hiring UAV aerial broadcast and 27–53 % of ROLMRT when hiring UAV spot-spraying. On the steep-slope vineyard, these values were 39–52 % in the UAV aerial broadcast scenarios and 36–46 % in the UAV spot-spraying scenarios. Revenue, variable and fixed costs, CAP payment amounts and ROLMRT are provided in **Supplementary Table S6** for the flat vineyard and **Supplementary Table S7** for the steep-slope vineyard.

Lastly, the competitiveness of vineyards adopting UAV spraying was analysed by estimating winegrape production costs in € tonne^{-1} (Fig. 2). These values accounted for fixed costs as well as opportunity cost of family labour. The latter were estimated to be €429–443 ha^{-1} yr^{-1} on the flat vineyard and €1,958–2,100 ha^{-1} yr^{-1} on the steep-slope vineyard. The larger values were for high disease pressure scenarios. In the UAV spraying scenarios, annual opportunity cost of family labour was €415–422 ha^{-1} on the flat vineyard and €1,760–1,856 ha^{-1} on the steep-slope vineyard. Despite the additional labour cost savings, winegrape production costs in the UAV spraying scenarios were always higher than in the corresponding ground spraying scenarios. When relying on UAV aerial broadcast at estimated fee levels, winegrape production costs increased by 2–7 % on the flat vineyard and by 2–3 % on the steep-slope vineyard. In the UAV spot-spraying scenarios, the increase was 1–5 % on the flat vineyard and 1 % on the steep-slope vineyard. On the flat vineyard, production costs were lower than the winegrape selling price of €720 tonne^{-1} regardless of pesticide spraying strategy in low disease pressure scenarios. However, when disease pressure was high, only the production costs in the UAV spraying scenarios exceeded this value. On the steep-slope vineyard, winegrape production costs were higher than

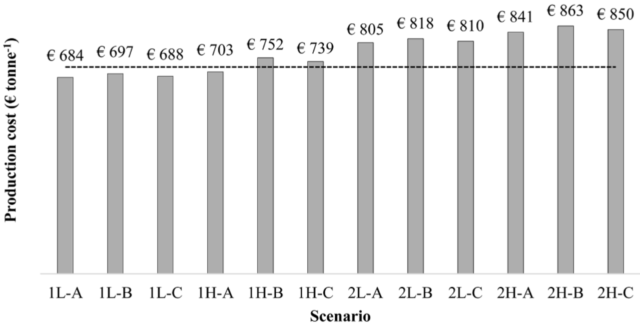

Fig. 2. Winegrape production cost by scenario. The dashed line corresponds to the assumed winegrape sales price of €720 tonne^{-1} [51].

€720 tonne^{-1} in all six scenarios considered. This indicates that steep-slope viticulture is challenged in the long term by a lack of mechanisation and consequent high labour inputs and that spray drone adoption at fees higher than €100 ha^{-1} does not improve its competitiveness despite potential cost and labour time savings.

4. Discussion

For the production-orientated farmer, the UAV spraying strategies were less desirable compared to ground equipment when assuming a €104–125 ha^{-1} custom-hired UAV fee. This was also the case when UAV spraying was assumed to reduce pesticide inputs by 50 % through spot-spraying and when the alternative pest treatment strategy was as labour intensive as backpack spraying. These results supported the hypothesis that UAV spraying would be currently less profitable than conventional vine spraying on both flat and steep-slope vineyards. A lower economic performance of UAV spraying is in agreement with previous economic studies in other perennial crops [23,32]. However, the present analysis was the first economic assessment assuming that UAV spraying would be custom-hired. Spray drone ownership was believed to be unlikely at the early adoption stage of UAV spraying in Greek viticulture, especially considering the presently high costs of the technology, the small mean vineyard size in Greece, and that UAV spraying is highly regulated and requires additional expenses such as software, licensing and medical certificates [11]. In Germany, where drone spraying has been allowed in steep-slope viticulture since 2022 [29], the majority of adopters hire UAV spraying services rather than owning a UAV [74]. Farmers tend to be gradual innovators [84] and custom-hiring would allow them to explore possible benefits before investing into a strictly regulated technology. Besides, operational complexity in flight planning and imagery data processing might also act as barriers to UAV ownership for small-scale farmers [8,9,12].

An important aspect that has been overlooked in previous UAV spraying economic analyses is a lower pest control efficacy in high disease pressure conditions. This has been identified in vineyards and may apply to other crops. In Switzerland, Dubuis and Jaquerod [18] found no statistically significant difference between ground and UAV treatments against powdery mildew when disease pressure was low, but the winegrape harvest was virtually lost when using a UAV in high disease pressure conditions. Conversely, treatments combining UAV spraying with complimentary ground equipment sprays were found to have a comparable efficacy to treatments solely based on the latter [18]. The authors also highlighted potential challenges when spraying contact fungicides against downy mildew because this pathogen penetrates the abaxial side of the leaf where UAV droplet deposition is lower [18]. Poss et al. [5] conducted a similar experiment in Germany and found no difference in pest control efficacy between UAV and ground spraying against downy mildew, but a higher incidence of powdery mildew bunch infections after UAV spraying treatments. Similarly to the Swiss experiment, the authors concluded that UAV spraying should be supplemented by land-based fungicide application in high disease pressure conditions [5]. Notably, ground spraying follow-ups have also been historically used in Italy after aerial application with crewed aircraft to ensure appropriate pest control in viticulture [85].

UAV spraying efficacy depends on a multitude of factors such as the degree of spray drift, pesticide droplet size, crop variety and phenotype, pathogen species, timeliness of operation and whether a PPP acts by contact or systemically. Despite this complexity, the currently available studies seem to agree that UAV spraying might complement existing practice rather than completely replacing it, especially in high disease pressure conditions [5,13,18]. In this analysis, ensuring the availability of ground equipment when hiring UAV spraying had the effect of further increasing the long-term monetary loss in high disease pressure scenarios, but less so on the steep-slope vineyard because backpack sprayers are inexpensive. To make UAV spraying more profitable than ground spraying, it was estimated that the UAV fee per hectare should not exceed €43 ha^{-1} on the flat vineyard in both low and high disease pressure scenarios and €42–49 ha^{-1} on the steep-slope vineyard depending on disease pressure level. These fees are much lower than the €104–125 ha^{-1} assumed for Greek vineyards and the €250 ha^{-1} currently charged in Germany [74], but they would be relatively similar to the cost of hiring UAV spraying in Australia, China and the US [19,21,75].

Nevertheless, lower UAV hiring fees might make it difficult for drone providers to run a viable business in the EU. Indeed, based on the weather parameters described in ISO 23117–1:2023 [40], spray drones would face considerable time constraints compared to ground equipment during spray months, thus limiting the capacity of drone providers to serve a large number of farms each year and achieve economic scalability. UAV good field days between April and July were six to eight in Attica and one to four in Crete, where a higher mean wind speed further restricted spray drone operation. In comparison, ground equipment could enter the fields on at least 27 days per month during the same period on both vineyards. Based on these values, it was estimated that UAV aerial broadcast with a single drone could serve 84 ha yr^{-1} in Attica and 15–29 ha yr^{-1} in Crete, with the latter range depending on disease pressure level. On the other hand, UAV spot-spraying could be hired on 126–169 ha yr^{-1} in Attica and 29–44 ha yr^{-1} in Crete. Easing visual-line-of-sight rules to allow the simultaneous use of multiple spray drones would improve the serving capacity of UAV providers. This is especially important in steep-slope viticulture, where weather tends to be less favourable, vineyards are smaller and difficult to access, and travel and UAV setup times may be higher.

With respect to annual labour inputs, UAV spraying resulted in savings of two to four farm operator days on the flat vineyard and 12 to 15 farm operator days on the steep-slope vineyard. The only scenario requiring seasonal labour was backpack spraying in high disease pressure conditions, where temporary workers were hired for 4 days in July. However, the labour savings reflected in the winegrape production costs were insufficient to compensate for the additional expenses for UAV hiring at the estimated fees. Production costs in the UAV scenarios were especially higher on the flat vineyard where savings in opportunity cost of family labour were lower because of the high work speed of vine spraying. On the steep-slope vineyard, UAV spraying could be beneficial if disease pressure was high and seasonal labour unavailable. Indeed, a sensitivity analysis assuming the absence of seasonal workers identified that UAV spraying would generate higher gross returns compared to backpack spraying by preventing the abandonment of 24 % of the vineyard in high disease pressure conditions. The latter is of particular relevance to Greece, where abandonment of permanent crops is the highest across the EU in terms of percentage of total agricultural land abandonment [4]. However, whether farmers facing unpredicted labour shortages in proximity of spray calendars would be able to promptly hire UAV spraying on the basis of a lack of “viable alternatives” [28: Art. 9 (2)] remains questionable from a practical standpoint.

As to the impact of UAV spraying on the environment, the results of the HFH-MOLP model leaned in favour of UAV spot-spraying because the environmental impact scores calculated following the PLI methodology depended on fungicide inputs per hectare. In other words, the environmental impact of pesticide spraying was reduced by an amount that was in linear proportion to the percentage of fungicides saved. Consequently, UAV aerial broadcast utilising ground equipment rates did not reduce the negative impacts of pesticide use on biodiversity, soil health and water. On the other hand, UAV spot-spraying reduced the environmental impact of pesticide spraying by 46–50 %, making it the preferred treatment strategy for the ecologically-orientated farmer and corroborating the second study hypothesis. However, UAV spot-spraying is affected by technical challenges because UAV remote sensing technology does not yet enable accurate disease detection to-date [8,9,12]. Besides, UAV imagery processing is complex, data intensive and time-consuming and generally handled by drone technology companies [12,15], which may result in untimely pesticide application and consequent yield losses. Therefore, pest prescription maps are generally produced by walking along the crop rows, thereby absorbing substantial labour inputs and making disease identification prone to human error. UAV spot-spraying or other variable rate technologies are the most straightforward approaches to reduce the environmental impact of pesticide spraying in conventional farming, but technological development is needed. In particular, profitability and pest control efficacy could substantially improve if drones were capable of conducting targeted pesticide applications in real-time and detecting fungal disease infections before they became visible to the human eye [13,15].

This study identified a clear benefit of UAV spraying in terms of a reduced impact on human health measured as level of operators' exposure to harmful substances. This was true regardless of disease pressure level and ground equipment type, thus supporting the third study hypothesis. The socially-orientated farmer obtained utilities of 86–95 % when adopting UAV spot-spraying and 77–91 % when hiring UAV aerial broadcast. This compared to the range of 68–84 % for conventional ground spraying equipment. A sensitivity analysis was conducted on the PL_{hh} indicator to test the minimum level of exposure reduction required for UAV spraying to halve the risk of pesticide use on human health to meet the objective of the European Green Deal and the EU Biodiversity Strategy for 2030. Compared to a vine sprayer, an exposure factor of 0.5 in low disease pressure conditions and 0.4 in high disease pressure conditions were sufficient to halve pesticide risk for farm operators in the absence of pesticide savings. The same reduction in the risk of pesticide exposure could be obtained with UAV pesticide savings of 50 % in low disease pressure conditions and 60 % in high disease pressure conditions even if UAV spraying resulted in exposure levels equivalent to a vine sprayer. Compared to a backpack sprayer, UAV exposure factors of 0.7 or pesticide savings of 30 % would be needed to halve the risk of human exposure to pesticides regardless of disease pressure. Considering the results by Kuster et al. [10] suggesting that drone-based spraying may reduce human exposure to pesticides by over 90 % compared to handheld equipment, UAV spraying could improve operators' safety in steep-slope viticulture even at ground equipment pesticide rates.

These findings imply that derogations for UAV spraying granted under Directive 2009/128/EC on the basis of a reduced impact on human health and the environment would be attainable when relying on UAV spot-spraying. However, spray drone operation remains challenged by several other normative texts which make the derogation system of Directive 2009/128/EC irrelevant to production-orientated and ecologically-orientated farmers. This is mainly due to a lower farm profitability both in the long and short term as a result of high UAV hiring fees and technical and regulatory barriers to UAV spot-spraying adoption to ensure a lower environmental impact. Besides, the estimated costs of hiring spray drones would increase the reliance of Greek vineyards on CAP payments by 1 % to 40 % on flat vineyards and by 5 % to 16 % on steep-slope vineyards. For spray drone providers, the challenges are related to the requirement of offering UAV spraying at lower fees, which may be infeasible in current weather and regulatory restrictions. To increase the servicing capacity of spray drone providers, regulations might allow to simultaneously fly multiple drones, utilise lower spray mix volumes, simplify licensing and approval procedures and possibly relax weather restrictions, especially for times when pollinators are less active (e.g., at night). These recommendations would be in agreement with the FAO's call for defining a balance between public safety and over-regulation of UAV spraying without impairing the development of private enterprise [24]. In its current status, EU regulation is impeding the exploitation of UAV spraying for farmers seeking to reduce risks associated to harmful substance use, to mitigate the effects of seasonal agricultural labour scarcity, and to continue winegrape production in abandonment-prone areas while decreasing reliance on public funding.

These implications have led European policymakers to address spray drones in a recent proposal to amend Directive 2009/128/EC. UAV spot-spraying was explicitly mentioned for the first time as an example where aerial spraying should be granted exemption [86]. This proposal maintained a general ban of aerial spraying in the EU but acknowledged that UAV aerial spraying was very likely to reduce the impact on human health and the environment, especially if UAVs could be used at early disease development stages [86]. The proposal also recognised the advantages of simultaneous operation of multiple drones [86]. However, the UAV spot-spraying derogation would have become effective three years after the enforcement of the eventual regulation, which would have prolonged the challenge of achieving a reduced impact on the environment via UAV spraying in the transition period. The proposal was eventually rejected in November 2023 by the European Parliament [87] and later withdrawn by the European Commission following farmers' protests in early 2024 [88]. Therefore, the legal status of UAV spraying in the EU remains controversial. In December 2024, this led 15 Member States to submit a formal request to the European Commission to establish more appropriate regulation on the basis that Directive 2009/128/EC did not consider the benefits of spray drones at the time of its adoption, especially given their technological advancement in recent years [89].

To bypass the current EU regulatory barriers, a different approach has been proposed by several researchers claiming that spray drones should be normatively distanced from operation with crewed aircraft. This is because UAV spraying is conducted at a much lower distance from the crop canopy, resulting in spray drift risk that is comparable to ground sprayers [90]. However, to-date, it is widely recognised that the hazards related to spray drones are still not sufficiently understood [9, 13,14]. For this reason, several European task forces are trying to assess their associated risks and develop protocols for their safe use in agriculture. These include the European Precision Application Task Force [91], which has formed a working group dedicated to spray drones in June 2024, and the Unmanned Aerial Pesticide Application System Task Force, composed of eight private companies aiming to collect pesticide drift and deposition data, standardise field trials, and develop best management practices [92]. In support of these efforts, public research should continue to produce findings simultaneously focusing on the economic, environmental and social implications of UAV spraying, possibly exploring a diverse range of field operations, production systems and geographical contexts [8].

The results of this analysis are for Greek vineyards and depend on several assumptions as well as on current UAV regulation in the EU. The main limitation of this analysis is the UAV custom-hiring fee assumed in the absence of citable estimates for Greece. If lower fees similar to countries such as Australia, China and the US were assumed, the economic performance of UAV spraying would considerably improve. Additionally, other factors might change the economics of UAV spraying in Greek viticulture in the future. For example, the profitability of UAV spraying may become higher than ground spraying if Greece adopted a pesticide tax system based on the PLI approach such as the one implemented by the Danish Government or if UAV spraying was incentivised through payments for ecosystem services and improved workers' safety. Likewise, the economic performance of spray drones may improve with technological progress leading to more durable batteries, higher output flow rates, faster speeds, larger spray tanks, improved communication technology, and increased data processing capacity coupled with simplified regulation and lower UAV purchase or hiring costs [9,13,15]. Some benefits of spray drone use were identified in terms of a reduced likelihood of vineyard abandonment in conditions of extreme labour scarcity. However, the HFH-MOLP model relied on a rigid fungal disease treatment calendar and might have therefore missed additional positive labour implications of UAV spraying as a result of pest load fluctuations in the short term or climate change in the long term. Besides, this analysis only focused on powdery and downy mildew and on conventional fungicide treatments. For example, drones might provide substantial economic and environmental benefits when used for the application of biologicals in organic farming (e.g., Aermatica3D [93]).

Lastly, the present study compared spray drones with conventional land-based sprayers, but other innovations such as the ICARO X4 robot controlling powdery and downy mildew with UV-C radiation [94,95] could be assessed in future research.

5. Conclusion

Despite spray drones receiving growing attention in the literature in recent years, this was the first analysis focusing on the regulatory implications of UAV spraying in Europe by simultaneously estimating farm profitability, environmental impact and farm operators' exposure to pesticides. Depending on fungal disease pressure, using a spray drone in Greek viticulture generated total cost savings in the range of €278–377 ha^{-1} on a flat vineyard and €367–538 ha^{-1} on a steep-slope vineyard. However, these savings did not compensate for the additional costs estimated for hiring UAV spraying. Thus, in line with previous studies, ground spraying was more profitable both in the short and in the long term and was characterised by more advantageous winegrape production costs. Additionally, spray drone adoption increased the reliance of Greek vineyards on CAP payments in all scenarios. Nevertheless, when seasonal labour was assumed to be unavailable, UAV spraying was found to provide economic benefits in steep-slope viticulture when disease pressure was high. This is of particular relevance to Greek viticulture in remote areas, where labour scarcity, farm marginalisation and subsequent land abandonment are widespread phenomena [4].

The results of this multi-criteria assessment of spray drone use in Greek viticulture highlighted that UAVs could mitigate some of the challenges currently faced by this sector while possibly providing environmental benefits and improving farm operators' safety. However, this will largely rely on the capacity of drone manufacturers to reduce technology costs and, particularly at the initial stages of adoption, on the economic feasibility for drone service providers to offer UAV spraying at fees in the range of €42–49 ha^{-1} similarly to those charged in countries such as Australia, China and the US. The latter may become possible if regulation allowed less constrained UAV operation, including simultaneous use of multiple drones or pesticide application with ultra-low spray mix volumes. Meanwhile, the present lack of PPPs approved for aerial spraying and technical development of practices such as spot-spraying should continue to be matter of priority for agrochemical companies and technology developers. This analysis showed that UAV spraying has the potential to lower operators' exposure to pesticides in conventional farming regardless of UAV spraying strategy. However, reducing the environmental impact of pesticide use requires drones to apply lower PPP inputs per hectare. This could for example be achieved via UAV spot-spraying, thereby diminishing the impact of pesticide use on biodiversity, soil and water by a proportion that is linearly correlated with the amount of pesticides saved. UAV aerial broadcast, which is to-date the most technically feasible UAV spraying strategy, was not the preferred choice for any of the modelled decision-maker types.

As long as UAV aerial spraying is strictly regulated in the EU, it remains questionable whether this technology could be enabled to contribute to the EU policy objective to achieve a 50 % reduction of pesticide use and risk by 2030. This analysis focused on possible UAV spraying scenarios under the derogation system established in Directive 2009/128/EC, whereby spray drones could be granted exceptional permissions in the absence of viable alternatives to ground spraying or if they produced benefits in terms of human health and environmental impact [28]. These permissions have been exploited in countries such as Germany [29] and Hungary [30], but they consist of lengthy, costly and complex procedures involving multiple authorities and thereby limiting large-scale adoption of UAV spraying in the EU. Whether legislation will catch up with UAV technology advancement and exploit its potential to contribute to a transition to agroecological farming in Europe will depend on the future course of policymaking action at the EU level and on the evidence being produced by task forces, private companies and public research globally.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Elias Maritan: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Evangelos Anastasiou:** Writing – review & editing, Methodology, Conceptualization. **Vasilis Psiroukis:** Methodology, Conceptualization. **James Lowenberg-DeBoer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Spyros Fountas:** Supervision, Funding acquisition. **Karl Behrendt:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2025.100837.

Data availability

The HFH-MOLP model code and related GAMS input spreadsheet files for each scenario are available in the supplementary materials included in the online version of this article.

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