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The magpie and the grapes: increasing ozone exposure impacts fruit consumption by a common corvid in a suburban environment

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Abstract

BACKGROUND: The Eurasian magpie *Pica pica* is a resident bird species able to colonize farmlands and anthropized environments. This corvid shows a wide trophic spectrum by including fruits, invertebrates, small vertebrates and carcasses in its diet. A camera-trap experiment was carried out to test the effect of different ozone (O_3) concentrations on potted *Vitis vinifera* plants, which resulted in different grape consumption rates by suburban birds. The test was performed at an Ozone-Free Air Controlled Exposure (FACE) facility, consisting of nine plots with three ozone (O_3) levels: AA (ambient O_3 concentration); and two elevated O_3 levels, 1.5× AA (ambient air with a 50% increase in O_3 concentration) and 2.0× AA (ambient air with a 100% increase in O_3 concentration). Camera-traps were located in front of each treatment area and kept active for 24 h day^{-1} and for 5 days at a time over a period of 3 months to monitor grape consumption by birds.

RESULTS: We collected a total of 38 videos. Eurasian magpies were the only grape consumers, with a total of 6.7 ± 3.3 passages per hour (mean ± SD) and no differences across the different O_3 treatments. Grapes in the AA treatment were consumed significantly more quickly than those in the 1.5× AA treatment, which in turn, were consumed faster than those in the 2.0× AA treatment. At 3 days from the start of treatment, 94%, 53% and 22% berries from the AA, 1.5× AA and 2.0× AA treatments had been eaten, respectively. When the O_3 was turned off, berries were consumed at the same rate among treatments.

CONCLUSION: Increasing O_3 concentrations limited grape consumption by magpies probably because O_3 acted as a deterrent for magpies, although the lower sugar content recorded in the 2.0× AA berries did not affect the consumption when O_3 was turned off. Our results provided valuable insights to mitigate human–wildlife conflicts in suburban environments.

Supporting information may be found in the online version of this article.

Keywords: corvids; crop pests; ozone-FACE; *Pica pica*; suburban environment

1 INTRODUCTION

Insects and other invertebrates represent the vast majority of crop pests; however, vertebrate species are also responsible for severe production losses in agriculture.[1–3] Among the vertebrates, birds may be a major cause of potentially high limitations to crop productivity,[4–7] despite being mostly regarded as regulators of arthropod pest.[8,9] The main bird families responsible for crop damage in temperate countries are the Passeridae, Columbidae, Sturnidae and Corvidae,[10,11] and most affect fruit production in orchards.[12–14] Among these, corvids (Passeriformes: Corvidae) are particularly concerning in Mediterranean agroecosystems,[15,16] because they have one of largest body sizes among Passeriformes and may include species living at high population densities.[17,18]

In particular, the Eurasian magpie *Pica pica* is adapted to a wide number of habitat types including farmland, forest edges and urban ecosystems,[16,19–21] which may in turn increase the risk for

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crop depredation in many environmental contexts.[22,23] Crop impacts by this bird species will increase in future because of the sharp upward trend in its European population.[24] Tall trees and the presence food are the main factors required by magpies for breeding, making this species a pioneer exploiter of new environments.[25–28] Conflicts with stakeholders mostly occur in farmland, particularly in suburban areas where magpie densities are the highest and in small-game hunting estates.[24,25]

Therefore, effective management strategies are needed to limit the impact of magpies on orchards. Most methods applied to date include species-selective trapping (e.g. mist-nets and Larsen traps[24,29]), biological control with eagle owls *Bubo bubo*, and other large-scale and unselective lethal methods; for example, poisoned bait, which is currently legally prohibited in most European countries.[30] Orchard protection by netting seems to be ineffective in the medium-long term for corvids, because nets can be easily displaced or damaged.[31] Several pesticides have been used as bird repellent (e.g., neem[32]; methiocarb[33,34]), and their effectiveness amongst corvids has recently been tested on carrion crows *Corvus cornix*.[15]

Grapevine (*Vitis vinifera* L.) has significant cultural, economic and ecological relevance in the Mediterranean. Moreover, grapevine has an economic value globally,[35] and wine production is an important economic activity and a pillar of the cultural identity of several countries across the world.[36] Magpies and other birds are known to consume grapevine berries (hereafter, berries[37]). The large number of studies already performed on climate change and viticulture (Santos *et al*. 2020) also include research on the impact of air pollutants on yield loss and grape quality,[35,38,39] particularly the concentration of soluble sugars, which closely correlates with grape productivity,[40] and the economic significance of vineyards in the global economy.[41,42] Despite this, there is little knowledge regarding the relationships between air pollutant levels and the consumption of fruits by birds.

Among air pollutants, ground-level ozone (O_3) is known to negatively affect both human health and terrestrial biodiversity, and is widespread both in urban and in natural areas,[43–47] although impacts on animal species remain widely underexplored.[48–50] Cuesta *et al*.[51] showed that O_3 exposure was associated with lung dysfunctions in rock pigeons, *Columba livia*, limiting their reproductive success. In addition, Reif *et al*.[50] reported an adverse effect of O_3 pollution on the fitness of the bluethroat, *Luscinia svecica*, and other birds in mountain ecosystems.

In our work, we applied a camera-trapping protocol already used to monitor grape consumption by bird pests (Lamelas-Lopez and Marco 2021) to test whether different O_3 concentrations would affect grape consumption by the Eurasian magpie.

2 MATERIALS AND METHODS

2.1 Plant material

The grapes investigated in this study were produced by *Vitis vinifera* cv 'Cabernet sauvignon', which is a hybrid derived from Berlandieri × Rupestris [775 P CFC 83/20] root stocks. The root stocks used in the experiment were obtained from Pierucci Agricoltura Estate (Tuscany, Central Italy). 'Cabernet sauvignon' products used in this experiment were grafted onto phylloxera-resistant rootstocks.[52]

A total of 36 plants were placed in 30-L pots to ensure sufficient space for root development and prevent growth limitations.[53] The potting soil mixture was based on the method described by Soja *et al*.[54] and consisted of a 1:1 ratio of sand and peat to avoid overwetting or soil compaction. Throughout the experimental period, plants were provided with adequate water to maintain optimal hydration levels. The watering regime aimed to meet 60% to 80% of daily evapotranspiration, amounting to 2.5 to 3.5 L of water per day.

Plants were subjected to O_3 exposure during three growing seasons, specifically from 21 May to 31 October 2020, from 10 June to 31 October 2021 and from 20 May to 31 October 2022. During the first year (2020), no berry was produced. In 2021, fructification was successful and animal consumption was recorded, although we were not able to identify what was consuming the grapes. Therefore, during the third year of O_3 exposure (2022), we decided to conduct a camera-trap experiment to determine which animal species was responsible for berry consumption.

2.2 Ozone experiment

The study took place at an O_3 Free Air Concentration Enrichment (hereafter, FACE) facility in Sesto Fiorentino (Central Italy, 43°48′ N, 11°12′ E and 55 m a.s.l.), which consists of nine 5 × 5 × 2 m plots in which the O_3 levels are measured and controlled.

An O_3 generator (TGOC13X, Triogen Ltd, Glasgow, UK) was used to produce O_3 from pure oxygen. The resultant O_3-laden air was mixed with ambient air in a mixing tank and introduced to the plant canopies *via* micro-holes in 25 Teflon tubes suspended vertically from an overhead grid at a height of 2 m above the plants in each plot.

The experiment involved three O_3 concentration levels: ambient air (AA), ambient air with a 50% increase in O_3 concentration (1.5× AA), and ambient air with a 100% increase in O_3 concentration (2.0× AA). Each O_3 treatment consisted of three plots, and within each plot, there were four plants. AA plots also had all the same air-releasing tubes as the elevated O_3 plots but these release ambient air with no added O_3, because differences in tubing system (and the noise from it) could have confounded all the results by introducing a methodological artefact. A total of three replicates ($n = 3$ plots) were considered for each treatment.

To ensure accurate measurement and regulation of O_3 emissions, a continuous monitoring system (Mod. 202, 2B Technologies, Boulder, CO, USA) was employed at canopy height to provide feedback for the proportional-integral-derivative algorithm, which regulated the O_3 emission by adjusting the valves.[52]

Throughout the experiment, environmental variables were monitored continuously by a Watchdog station (Mod. 2000; Spectrum Technology, Inc., Aurora, IL, USA) located at 2.5 m above ground level (a.g.l.). The station collected data on precipitation, photosynthetic active radiation, wind speed and direction, air temperature, and relative humidity.

2.3 Sampling survey

When the berries reached the veraison phase (day of the year (DOY) 210–215 in the Mediterranean basin[55]), all of them were enclosed within a gentle plastic covering to protect the fruits against the pests until the berries reached maturity. We conducted two try-outs during the fruit maturation period in which a set of plants had their bunches uncovered to permit berry consumption.

In the first period, from 1 to 5 September, we turned off the O_3 emission system (No O_3 trail) and counted the berries in each bunch to evaluate the daily percentage consumption in all O_3 treatments, conducting 5 days of observation. In the second try-out, between 12 and 16 September, we turned on the O_3 emission system (O_3 trail) and conducted the same observation as in the first try-out.

Three camera-traps (©Browning SpecOps) were placed at about 130 cm a.g.l., oriented towards potted vineyard plants in all O_3 treatments. The traps were kept active for 24 h day^{-1}, to take one video (1 min) per animal passage (inter-video lag: 5 s). Camera-traps were checked once a day to download data and change dead batteries. Moreover, every morning of each 5-day sampling period, we counted the number of magpie passages above each O_3 treatment for 1 h (from 07.00 am to 08.00 am, solar hour).

2.4 Patterns of activity rhythms of the Eurasian magpie

For all magpie videos, we reported date and solar hour as shown directly on each video. The use of solar hours allows better evaluation of activity patterns because, in contrast to the 'legal hour', it is defined by the position of the sun in the sky, regardless of the local time, which varies among seasons. We counted as 'independent events' all videos of magpies taken by the same camera-trap over a time span of ≥ 30 min.[56] When more than one magpie video was recorded by the same camera-trap in ≤ 30 min, we kept only one record in our data set only, placed in the mid-time between the first and the last video.

2.5 Determination of grape soluble sugars and organic acids

At the end of the experimental period, $n = 100$ berries from at least three plants per plot were collected, immediately placed in liquid nitrogen, and stored at −80 °C until biochemical analyses.

Soluble sugars (glucose and fructose) and organic acids (citric, malic and tartaric acids) were determined according to Pisuttu *et al.*,[57] with minor modifications as follows. After extracting around 50 mg of lyophilized grapes with 100% high-performance liquid chromatography (HPLC)-demineralized water, the compounds were eluted by an ultra-HPLC (UHPLC) using a Dionex UltiMate 3000 system (Thermo Fisher Scientific, Waltham, MA, USA) equipped with a pre-column Repromer H [8 mm internal diameter (id) × 20 mm length, 9 μm particle size] and a Repromer H column (8 mm id × 300 mm length, 9 μm particle size), using 9 mM sulfuric acid as the eluent and a flow rate of 1 mL min^{-1}. Sugars were detected using a refractive index detector RefractoMax 520 (DataApex, Prague, Czech Republic), whereas organic acids were detected by their absorbance at 210 nm using a Dionex UVD 170 U detector (Thermo Fisher Scientific). To quantify their content, known amounts (0.003–0.5 mg mL^{-1}) of pure standards (Sigma-Aldrich, St. Louis, MO, USA) were injected into the UHPLC system and an equation correlating the peak area with compound concentration was formulated.

2.6 Statistical analysis

Daily and hourly O_3 average concentrations were used to compare O_3 levels along the two try-outs.

The consumption of berries from each trial ('No O_3' and 'O_3') was analysed using repeated measures one-way analysis of variance (ANOVA), using days of observation (*D*) as the 'within factor' and O_3 treatment as the 'between factor', having tested for normal distribution of data.

Least significant difference (LSD) post-hoc tests were conducted considering the interactions between treatments and observation days ($P < 0.05$). The quality of berries was compared using one-way ANOVA with treatment as the factor to evaluate the effect of O_3 on soluble sugar and organic acid contents. Both analyses were performed using STATISTICA version 7.[58]

The number of passages across different treatments was computed for each treatment over a 5-day period. Comparative analysis of the means among the three treatments was subsequently performed using a χ^2 test.

We used R software (version 3.6.1., R Foundation for Statistical Computing, Vienna, Austria: www.cran.r-project.org), package '*overlap*'[59] to estimate the patterns of activity rhythms of the Eurasian magpie. Hermans–Rasson *r* test was computed using the package '*CircMLE*',[60] to assess whether the magpies showed a random activity pattern over hours of captures.[61]

3 RESULTS

3.1 Observed bird species

Birds observed in the study area included Eurasian magpie *Pica pica* as the most abundant species, followed by common pheasant *Phasianus colchicus*, rock pigeon *Columba livia* forma *domestica*, wood pigeon *Columba palumbus*, European bee-eater *Merops apiaster*, kestrel *Falco tinnunculus*, ring-necked parakeet *Psittacula krameri*, Eurasian hoopoe *Upupa epops*, green woodpecker *Picus viridis*, common sandpiper *Actitis hypoleucos*, night heron *Nycticorax nycticorax*, barn owl *Tyto alba*, short-eared owl *Asio flammeus* and several species of small Passeriformes (Eurasian blackbird *Turdus merula*, European starling *Sturnus vulgaris*, dunnock *Prunella modularis*, Eurasian robin *Erithacus rubecula*, long-tailed tit *Aegithalos caudatus*, black redstart *Phoenicurus ochruros*, European serin *Serinus serinus*, Italian sparrow *Passer italiae*, zitting cisticola *Cisticola juncidis*, European goldfinch *Carduelis carduelis*, Eurasian golden oriole *Oriolus oriolus* and common chiffchaff *Phylloscopus collybita*).

3.2 Observation of Eurasian magpie and berry consumption

We collected a total of 38 magpie videos. Eurasian magpies were the only grape consumers, with a total of 6.7 ± 3.3 passages per hour (mean ± SD). There were no significant differences between vineyards and O_3 treatments ($\chi^2 = 102$, $P < 0.01$) (Fig. 1(A)).

Other species detected by camera-traps around berries (but not eating them) included the common pheasant ($n = 3$ videos), the rock pigeon ($n = 3$ videos) and the European brown hare *Lepus europaeus* ($n = 1$ video). The activity of the Eurasian magpie at the vineyards peaked immediately after sunrise: in other words, activity patterns were significantly different from a random pattern, according to the Hermans–Rasson test ($r = 67.29$, $P < 0.001$) (Fig. 1(B)). We pooled magpie videos from all O_3 treatments to compute the actual diurnal activity peak of the species.

During the No O_3 trail, no difference was observed regarding the pattern of berry consumption among treatments (Fig. 2(A)), although statistical differences were detected among the days with the birds consuming all available berries in 2.0× AA after 5 days of observation. During this try-out, the O_3 was turned off and daily and hourly O_3 average levels were almost the same among the treatments (Fig. 2(C),(D)) with average O_3 levels of 28.9 parts per billion (ppb) at AA, 31.6 ppb at 1.5× AA, and 28.1 ppb at 2.0× AA treatment (Table 1).

In the O_3 try-out, the interaction among factors, treatment and days was statistically significant (Fig. 2(B)). Berries in the AA treatment were consumed significantly more quickly than those in the 1.5× AA treatment, which were, in turn, consumed faster than those in the 2.0× AA treatment. For instance, after 3 days of exposure to O_3 treatments, 94%, 53% and 22% of berries from the AA,

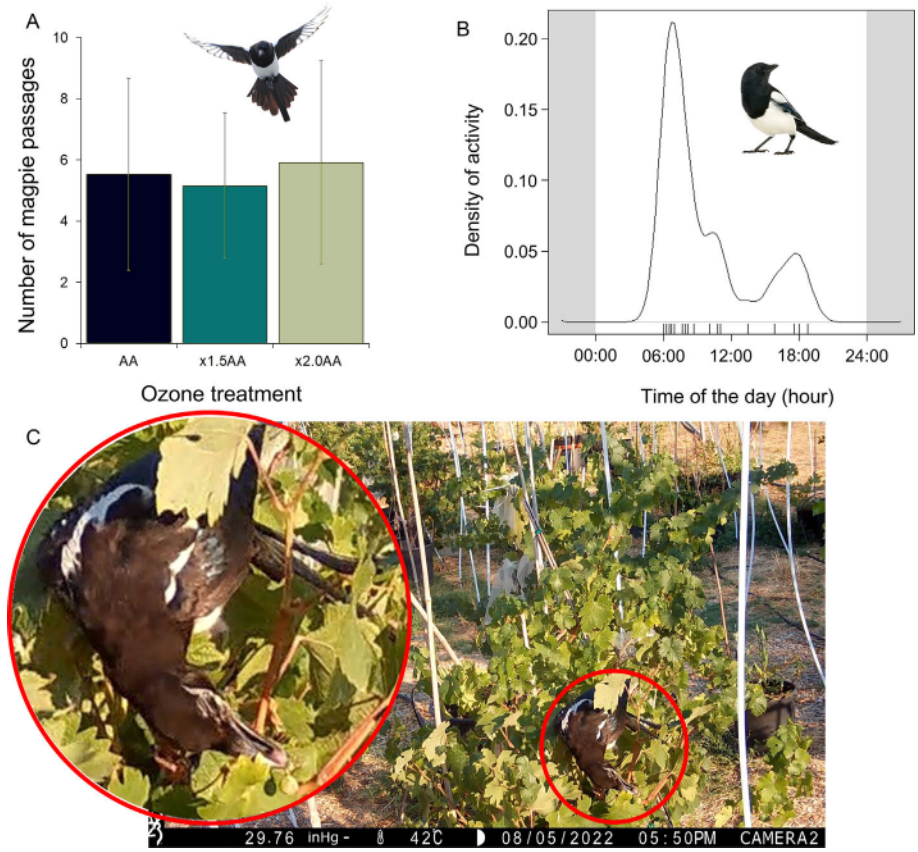

Figure 1. (A) Number of magpie passages (mean ± SD) above each ozone (O_3) treatment, where AA is ambient O_3. (B) Patterns of magpie activity rhythms over 24 h. (C) A magpie picking grapes at the O_3-FACE.

1.5× AA and 2.0× AA treatments were eaten, respectively. After 5 days (end of the observation), all the berries in the AA treatment were consumed, whereas in the 2.0× AA treatment more than 50% of the berries remained. During this try-out, the differences in daily and hourly (Fig. 2(E),(F)) O_3 average levels among the treatments were clear, with average O_3 levels of 31.3 ppb at AA, 46.7 ppb at 1.5× AA and 59.7 ppb at 2.0× AA treatment (Table 1).

Regarding the O_3 distribution during the day (Fig. 2(D), (F)), we observed a pattern with the lowest O_3 level in the early morning (hourly average of 12.94 ppb from 05:00 am to 09:00 am), reaching the lowest values at around 07:00 am (7.23 ppb hour average along both trails recorded at 07:00 am). After 09:00 am, we recorded an increase in O_3 concentration with the highest levels registered in the afternoon (hourly average of 57.02 ppb, from 03:00 pm to 06:00 pm), and the maximum occurring around 05:00 pm (hourly average of 56.88 ppb). This pattern was fixed by the O_3 emission system once the automatic control had been programmed to start when AA O_3 is above 15 ppb.

3.3 Berry quality

The glucose and fructose content was statistically different among the treatments, whereas this difference was not observed for organic acid content (tartaric, citric and malic acids) (Table 2). A reduction trend was observed for the glucose content, whereas the fructose content declined only in the 2.0× AA treatment compared with AA and 1.5× AA O_3 levels (Fig. 3). The sugar content in berries was the same as observed in the previous year (2021, mean ± SD = 21.52 ± 2.05°Bx; 2022, mean ± SD = 19.94 ± 2.10°Bx).

4 DISCUSSION

Magpies were the only crop-pest bird recorded feeding on grapes in our experiments, possibly because their natural circadian rhythms peak in early morning, immediately after sunrise (Fig. 1); when the O_3 concentration at our study site was lowest. In fact, the activity of the Eurasian magpie in nearby vineyards without O_3 treatments peaked immediately after sunrise (Supporting Information, Fig. S1), which is a typical trend in activity rhythms throughout the 24-h cycle as observed for this species in natural feeding areas.[62] This indicates that magpies exhibited non-random behaviour and were most likely feeding in the early morning. However, the O_3 concentration may have also played a role in influencing magpie behaviour, because the experimental plots exhibited low hourly averages overlapping with the peaks of maximum Eurasian magpie activity. Conversely, the activity decreased drastically during the central hours of the day, coinciding with the exponential increase in O_3 concentrations.

In recent years, it has emerged that the olfactory system in birds is a well-developed and fundamental sense for trophic activity.[63–65] However, under normal environmental conditions, O_3 is odourless,[66] producing a pungent smell only at very high concentrations.[67] This may help explain why magpies avoided the 2.0× AA plot. We excluded local anthropogenic noises (e.g. those produced by the irrigation system and by the O_3-FACE facility, which were the same ones perceived in all treatments) as factors explaining the 2.0× AA treatment avoidance by magpies.

However, despite a similar passage rate among the different O_3 treatments, the low grape consumption rate by magpies in the 2.0× AA treatment might be explained as an experience-learned

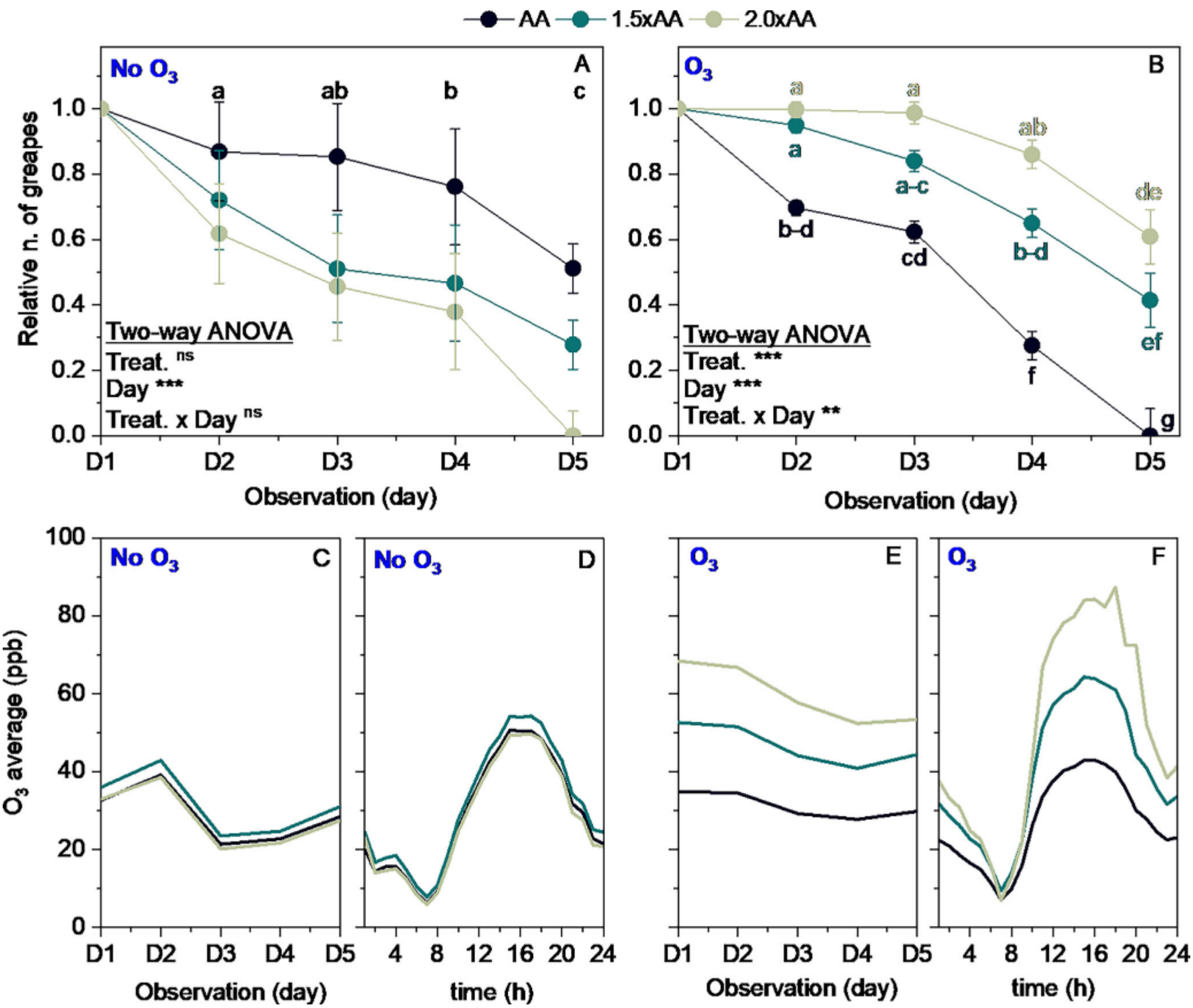

Figure 2. Relative number of berries during 5 days of observation during both try-outs: (A) O_3 turned off ('No O_3'; before treatments), (B) with O_3 system on ('O_3'). Values are the average ± SE. $n = 3$. Differences among treatments and times are represented by a lowercase letter (repeated measures one-way analysis of variance, LSD post-hoc test; $P < 0.05$). (C, D) Profiles of environmental O_3 concentrations on different days and hours under the no O_3 condition. (E, F) Profiles of environmental O_3 concentrations on different days and hours with O_3 on. AA, ambient air; 1.5× AA, ambient air with a 50% increase in O_3 concentration; 2.0× AA, ambient air with a 100% increase in O_3 concentration. $^{**}P < 0.05$; $^{***}P < 0.01$.

Table 1. Analysis of variance (ANOVA) results used to evaluate differences in the consumption of berries in the different O_3 treatments

	No O_3 trail						O_3 trail					
ANOVA	Intercept	Treatment	Error	Day	Day × Treatment	Error	Intercept	Treatment	Error	Day	Day × Treatment	Error
df	1	2	9	3	6	27	1	2	9	3	6	27
F ratio	54.88	2.45		14.72	0.59		999.87	43.16		103.31	3.68	
P value	0.000	0.142		0.000	0.737		0.000	0.000		0.000	0.008	

Note: Data are shown as mean ± SE, $n = 3$. Differences among treatments are indicated by lowercase letters (LSD test, $P < 0.05$); df, degrees of freedom.

behaviour.[68] In other words, magpies may have disliked the berries or air when the O_3 generator was switched on in the 2.0× AA treatment; also avoiding it when the generator was turned off.

The O_3 exposure in our study site lasted for 3 years, and magpies are intelligent birds that learn through training. The same changes in berry biochemical composition might have occurred also in the previous year, and this would lead to the development

Table 2. Analysis of variance (ANOVA) results used to evaluate the differences in soluble sugars (glucose and fructose) and organic acids (tartaric acid, citric acid and malic acid) in the different O_3 treatments

O_3 treat.	Glucose	Fructose	Tartaric acid	Citric acid	Malic acid
AA	296.24 ± 9.07 a	446.91 ± 8.86 a	21.66 ± 1.40 a	7.30 ± 1.55 a	1.52 ± 0.24 a
1.5× AA	284.82 ± 2.14 ab	432.78 ± 6.00 a	23.65 ± 2.12 a	5.55 ± 1.01 a	1.11 ± 0.17 a
2.0× AA	257.86 ± 11.28 b	372.23 ± 15.16 b	24.25 ± 0.92 a	8.62 ± 0.25 a	1.17 ± 0.17 a

ANOVA	Intercept	Treatment	Error	Intercept	Treat ment	Error	Intercept	Treat ment	Error	Intercept	Treat ment	Error	Intercept	Treat ment	Error
df	1	2	6	1	2	6	1	2	6	1	2	6	1	2	6
F ratio	3287.93	5.44		4552.45	13.71		662.27	0.75		131.63	2.03		124.51	1.25	
P value	0.000	0.045		0.000	0.006		0.000	0.511		0.000	0.212		0.000	0.350	

Note: Data are shown as mean ± SE, $n = 3$. Differences among treatments are indicated by lowercase letters (LSD test, $P < 0.05$). AA, ambient air; 1.5× AA, ambient air with a 50% increase in O_3 concentration; 2.0× AA, ambient air with a 100% increase in O_3 concentration; df, degrees of freedom.

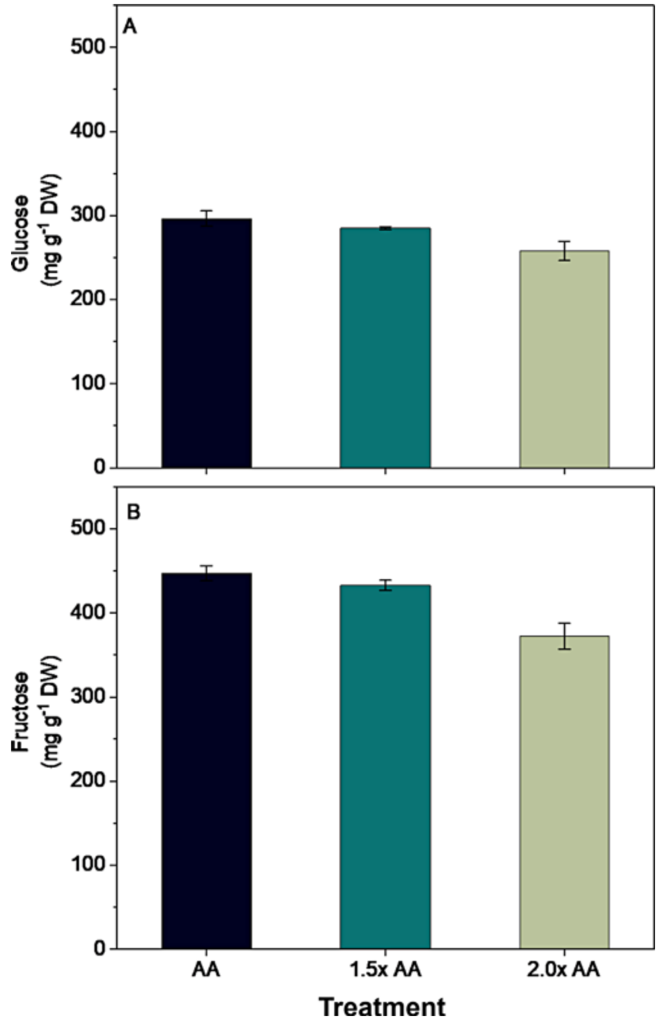

Figure 3. Content of glucose (A) and fructose (B) in the berries of *Vitis vinifera* in the three O_3 treatments. Differences among treatments were significant (LSD test; $P < 0.05$). DW, dry weight; AA, ambient air; 1.5× AA, ambient air with a 50% increase in O_3 concentration; 2.0× AA, ambient air with a 100% increase in O_3 concentration.

of attained knowledge, thus affecting magpie behaviour in the third year. This sort of behavioural adaptation may represent one of the potential factors affecting our observations. O_3 concentration was low during the early morning, and there was no noise when the O_3 generator was off. Conversely, peaks in O_3 concentration and O_3 generator noise during other hours of the day may have led magpies to avoid the study area in the early morning.

Furthermore, in the 2.0× AA treatment, the soluble sugars in the berries (attractants for magpies[69]) decreased significantly, with no change in organic acids, resulting in a less pleasant taste that might have kept the magpies away.[69,70] In fact, birds are usually attracted by coloured, well-ripened fruits, rich in natural sugars. A decrease in sugar concentration, therefore, makes fruits less palatable for frugivore birds[69,70] and insects.[71] Despite this, when the O_3 was turned off, fruits were consumed at similar rates among plots in our study. Thus, the distress of the respiratory system was most likely the main factor affecting fruit consumption by magpies in O_3-enriched plots.[50,51,72,73] It is known that O_3 stress significantly impacts plant physiological and biochemical processes in crop species, including accelerated leaf senescence, disrupted photosynthesis and biochemical status,[74–78] inhibited plant growth and development,[79–81] imbalances in aboveground and underground biomass,[82] and perturbed carbon and nitrogen transport.[71,83] These changes ultimately lead to a deterioration in fruit quality.[84]

5 CONCLUSIONS

Although effective tactics to keep corvids away from crops in the long term have not been described previously, this study provided valuable insights to mitigate human–corvid conflict in agricultural and suburban environments. This may be particularly interesting also for other crop-pest bird species with challenging management and intriguing adaptive abilities in rhythms and coexistence. Examples of such adaptation can be found in several bird species occurring in suburban areas, such as the Eurasian starling and the ring-necked parakeet, an exotic species of significant management concern, well adapted to our study area and sharing its feeding habitat with the Eurasian magpie.[68,85,86]

O_3 treatment had a considerable impact on the berries, especially in terms of their soluble sugar content, which decreased, whereas the concentration of organic acids did not change. The alteration in the chemical composition can result in lower palatability of the fruits, potentially discouraging magpies from eating them, because magpies are naturally attracted by coloured, well-ripened fruits, rich in natural sugars.[69,70,87] This drop in sugar concentration highlights a potential effect of O_3 pollution on birds and cash crops, in addition to the previously documented avoidance.[72]

Our results offer an insight into some effects of O_3 pollution on wildlife and agriculture. This environmental pollutant not only has an impact on bird health owing to changes in food availability and respiratory health, but also represents a remarkable threat to agricultural yield and fruit quality. Assessing the possible cascading impacts of O_3 pollution on ecosystems and human food resources is critical to create effective mitigation methods and ensuring a healthy and sustainable environment. More research and collaboration among scientists, governments and industry are required to address this environmental challenge to preserve both wildlife and human activities by reducing conflict.

Given the increasing incursions and invasions by native pests and exotic alien species, the identification of O_3-resistant cultivars and carefully calibrated O_3 treatments with concentrations tailored to each agricultural species of interest could potentially serve as a deterrent for O_3-sensitive wildlife species. This approach may particularly benefit small-scale farmers, potentially leading to reduced crop losses.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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