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Authors: Kanatas, Panagiotis, Antonopoulos, Nikolaos, Gazoulis, Ioannis, and Travlos, Ilias S.

Source: Weed Science, 69(6) : 704-718

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wsc.2021.55

Weed Science

www.cambridge.org/wsc

Screening glyphosate-alternative weed control options in important perennial crops

Panagiotis Kanatas[1], Nikolaos Antonopoulos[2], Ioannis Gazoulis[2] and Ilias S. Travlos[3]

[1]Teaching Staff (P.D. 407/80), Department of Crop Science, University of Patras, Mesolonghi, Greece; [2]Ph.D. Candidate, Agricultural University of Athens, Faculty of Crop Sciences, Athens, Greece and [3]Assistant Professor, Agricultural University of Athens, Faculty of Crop Sciences, Athens, Greece

Research Article

Cite this article: Kanatas P, Antonopoulos N, Gazoulis I, Travlos IS (2021) Screening glyphosate-alternative weed control options in important perennial crops. Weed Sci. **69**: 704–718. doi: 10.1017/wsc.2021.55

Received: 25 May 2021
Revised: 30 July 2021
Accepted: 30 July 2021
First published online: 24 August 2021

Associate Editor:
William Vencill, University of Georgia

Keywords:
Cover crop residue; cycloxydim; flazasulfuron; mowing; oxyfluorfen; pelargonic acid

Author for correspondence:
Ilias S. Travlos, Agricultural University of Athens, Faculty of Crop Sciences, 75, Iera Odos str., GR11855, Athens, Greece.
(Email: travlos@aua.gr)

Abstract

The current study aimed to screen glyphosate-alternative weed control methods in three perennial crops in Greece. Field trials were conducted and repeated (2018 to 2019 and 2019 to 2020) in a citrus orchard (*Citrus clementina* Hort. ex Tan), an olive grove (*Olea europaea* L.), and a vineyard (*Vitis vinifera* L.) under the randomized complete block design (nine treatments, four blocks). Glyphosate was applied in the citrus orchard (720 g ae ha^{-1}), the olive grove (720 g ae ha^{-1}), and the vineyard (1,800 g ae ha^{-1}). Pelargonic acid (1,088 g ha^{-1}; two times), barley (*Hordeum vulgare* L.) residues and white mustard (*Sinapis alba* L.) residues were evaluated in all sites. Mowing was evaluated in the citrus orchard (one time) and the vineyard (two times). Flazasulfuron (50 g ha^{-1}), oxyfluorfen (144 g ha^{-1}), and flumioxazin (150 g ha^{-1}) were applied in the citrus orchard and the olive grove. Penoxsulam + florasulam (15 + 7.5 g ha^{-1}) was also applied in the olive grove. Cycloxydim (200 g ha^{-1}), quizalofop-*p*-ethyl (150 g ha^{-1}) and propaquizafop (150 g ha^{-1}) were applied in the vineyard. An untreated control was included in all sites. Flazasulfuron, oxyfluorfen, and flumioxazin resulted in similar normalized difference vegetation index (NDVI) and weed biomass to glyphosate in the citrus orchard in both years and evaluations. Pelargonic acid (two times) and mowing (one time) were effective on broadleaf weeds. Flazasulfuron and penoxsulam + florasulam were the most promising glyphosate-alternative weed control methods against hairy fleabane [*Conyza bonariensis* (L.) Cronquist] in the olive grove. Cover crop residues showed their suppressive ability as in the citrus orchard. All selective herbicides resulted in similar NDVI and johnsongrass [*Sorghum halepense* (L.) Pers.] dry weight values in the vineyard in both years. Negative and strong correlations were observed in all sites and years between crop yield and weed dry weight ($R^2 = 0.543$ to 0.924).

Introduction

In perennial cropping systems, weed presence contributes to soil conservation, improves soil fertility, and provides food and shelter to beneficial organisms (Mia et al. 2020). However, weed management is an essential agronomic practice in fruit orchards and vineyards (Onen et al. 2018; Travlos et al. 2018). Weeds can act as pathogen and insect pest hosts (Ligoxigakis et al. 2002; Thanou et al. 2021). Left uncontrolled, weeds can be established in high densities between tree rows and trees in the row and compete with the growing trees for water and nutrients (Mia et al. 2020). Weed competition during crucial growth stages can affect tree establishment, limit fruit production, and downgrade product quality (Mia et al. 2020; Travlos et al. 2018; Tursun et al. 2018).

In the European Union (EU), and indeed worldwide, the use of glyphosate remains by far the most common and effective practice for controlling weeds in perennial orchards (Duke and Powles 2008; Kudsk and Mathiassen 2020). Glyphosate is a nonselective, systemic herbicide acting as an inhibitor of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) of the shikimic acid pathway. It is the world's most important herbicide, with unique properties such as its excellent uptake and translocation and its toxicologically and environmentally safe profile (Duke and Powles 2008). This herbicide had a prominent role on the adoption of minimum-tillage and no-till cropping systems that maximized crop productivity even in semiarid lands where tillage leads to soil erosion and degradation (Farooq et al. 2011). In perennial orchards and fallow areas, it is the only herbicide that can be applied to perennial weeds at late growth stages and still be effective (Miller et al. 1998). For all these reasons and more, glyphosate has been highlighted as the once-in-a-century herbicide (Duke and Powles 2008). However, the agricultural sector seems to be overreliant on this specific herbicide. Consecutive applications in perennial orchards and fallow areas pose a common phenomenon during the last decades and have resulted in the spread of glyphosate-resistant weed populations. This is noted especially for the fruit orchards and vineyards of the Mediterranean region (Tahmasebi et al. 2018; Travlos and Chachalis 2010; Travlos et al 2020a; Vazquez-Garcia et al. 2020). Consequently, glyphosate applications should be integrated with nonchemical weed control practices, while alternative herbicides with different modes of action should be also evaluated (Scavo and Mauromicale 2020; Travlos et al. 2019). Moreover, although glyphosate has lower environmental impact compared with other herbicides and there is not a causal association between glyphosate and genotoxicity to humans (Duke 2020), the strict EU legislation for pesticides creates concerns regarding glyphosate's future in Europe (Beckie et al. 2020; Fogliatto et al. 2020). To maintain efficacy over time and partially counterbalance the economic consequences of the worst-case scenario (glyphosate phase-out), alternative weed management strategies should be investigated in the perennial orchards of Europe (Fogliatto et al. 2020; Kudsk and Mathiassen 2020).

Glyphosate-alternative weed control strategies rely first upon pre- or early postemergence herbicides with soil residual activity that enable long-term weed control with a single application and the applications of selective herbicides on targeted weed species that have dominated a particular field (Scarabel et al. 2014; Tahmasebi et al. 2018; Travlos et al. 2014). Natural contact, burndown herbicides can also contribute to solutions for the management of annual weed species (Muñoz et al. 2020; Young 2004). Mowing operations are also among the recommended agronomic practices that reduce weed growth and the reproductive ability of a various weed species (Butler et al. 2013; Mia et al. 2020). Winter-grown cover crops can outcompete weeds during the winter period. Moreover, the presence of their residues on the soil surface after cover crop termination can suppress the growth of summer weeds in the orchard (Alcántara et al. 2011; Tursun et al. 2018). All these practices have the potential to be combined with glyphosate applications in a rotational view under the concept of integrated weed management (Gerhards and Schappert 2020; Raimondi et al. 2020). It should be noted that in several studies in which glyphosate-resistant weed populations were reported, alternative herbicides were tested for weed control (Tahmasebi et al. 2018; Travlos and Chachalis 2010; Travlos et al 2020a; Vazquez-Garcia et al. 2020). However, research is also needed to evaluate alternative weed control methods in fields where glyphosate is still effective to get an estimation of the strengths and the weaknesses of any alternative strategy compared with glyphosate.

The objective of the current study was to conduct an initial screening of glyphosate-alternative weed control options in three important perennial crops in southern Greece. Field trials were conducted to evaluate the efficacy of the alternative weed control strategies in comparison with glyphosate. Alternative herbicides currently registered and available to farmers in the EU were tested. Mechanical weed control and treatments related to cover crop residue management were also evaluated.

Materials and Methods

Site Description

Field trials were conducted in a citrus orchard (*Citrus clementina* Hort. ex Tan, 'Marisol'), an olive grove (*Olea europaea* L., 'Koroneiki'), and a vineyard (*Vitis vinifera* L., 'Merlot') in southern Greece. Each separate trial was conducted during 2018 to 2019 and repeated during 2019 to 2020. New plots were established in new areas of the sites in 2019 to 2020 to repeat each experiment in time. The citrus orchard was located outside Pyrgos, Elis (37.644°N, 21.473°E). Soil type was loam. Soil texture (0 to 30 cm) was: 24.7% clay, 39.8% silt, and 35.5% sand, with a pH of 7.3 and 1.6% organic matter content. The trees were 7-yr-old, grafted onto 'Swingle citrumelo' rootstock (*Citrus paradisi* Macf. × *Poncirus trifoliata* L. Raf.), spaced 4.5 by 4.5 m apart, and under a drip-irrigation system. The dominant weed species were barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], common lambsquarters (*Chenopodium album* L.), black nightshade (*Solanum nigrum* L.), and redroot pigweed (*Amaranthus retroflexus* L.) and were highly persistent for both years.

The olive grove was located in Kyparissia, Messinia (37.227°N, 21.632°E). Soil type was sandy loam. Soil texture (0 to 30 cm) was: 18.1% clay, 28.3% silt, and 52.9% sand, with a pH of 7.6 and 1.4% organic matter content. The trees were 13-yr-old, self-rooted, spaced 6 by 6 m apart, and grown under rainfed conditions. For both years, hairy fleabane [*Conyza bonariensis* (L.) Cronquist] dominated this site. The vineyard was located in Korakochori, Elis (37.676°N, 21.310°E). Soil type was sandy clay loam. Soil texture (0 to 30 cm) was: 28.4% clay, 25.1% silt, and 46.5% sand with a pH of 7.5 and 1.3% organic matter content. The vines were 5-yr-old, grafted onto '1103 Paulsen' rootstock, and under a drip-irrigation system. Row spacing was 2.20 m. Vine spacing was 1.25 m. Johnsongrass [*Sorghum halepense* (L.) Pers.] was the dominant species in this site for both years. Similar climatic conditions prevailed in the experimental fields during both years (Table 1). This was expected for Elis fields and also for the olive grove, as it is located in the northwestern part of Messinia, neighboring the Elis district.

Experimental Setup

Herbicide application and the management of two cover crops' residues were common weed control treatments in all trials. All herbicides were applied with a pressurized Gloria® 405 T sprayer (Gloria Haus & Gartengeraete GMBH, Witten, Germany) calibrated to deliver 300 L ha^{-1} of spray solution at constant pressure through five 8002 flat-fan spray nozzles (spray angle: 80°). Direct spraying was carried out between rows and plants in the row. Details regarding herbicide products used in each field are presented in Table 2. Cover crop establishment and termination procedures were also the same in all sites. Barley (*Hordeum vulgare* L., 'Finola') (K+N Efthymiadis S.A., Thessaloniki, Greece) and white mustard (*Sinapis alba* L., 'Iris') (Vandinter Semo B.V., Scheemda, Groningen, The Netherlands) were selected, due to evidence suggesting the suppressive ability of their residues on summer weeds (Dhima et al. 2006; Didon et al. 2014). Seedbed preparation included tillage to 20-cm depth with a harrow pass and fertilizer incorporation with 50 kg ha^{-1} N and 60 kg ha^{-1} P_2O_5. Seeds were drilled at 0.5-cm depth. Seeding rates were 140 and 30 kg ha^{-1} for barley and white mustard, respectively. Rows were spaced 20 cm apart. Cover crop establishment was carried out in early October for both years. Termination was done by mowing in mid-April (Table 3). Cover crop residues were left on the soil surface to suppress summer weeds. Mowing was also a common weed control treatment in the citrus orchard and the vineyard. An intermediate-type mower with hydraulic motion control, 35 HP power, and 150-cm mowing width (OMA SGK/S 150, Panagrotiki S.A., Lamia, Greece) was towed on the field. Untreated plots were also included in all trials.

A randomized complete block design (RCBD) with nine treatments and four blocks (replications) was established in the citrus orchard. Treatments included the applications of glyphosate, pelargonic acid (two times), flazasulfuron, oxyfluorfen, flumioxazin, mowing (one time), barley residue management, white mustard

Table 1. Mean monthly temperature (C) and overall monthly precipitation (mm) at each site during 2018–2019 and 2019–2020.

		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Site	Parameter[a]	2018–2019											
Pyrgos	Mean T (C)	24.7	20.8	16.6	11.7	9.5	9.0	13.7	16.3	18.4	25.7	27.1	28.4
	Rainfall (mm)	39.8	17.0	168.6	106.0	180.8	95.5	60.6	85.8	15.6	0.8	5.4	0.0
Kyparissia	Mean T (C)	25.0	21.1	17.3	12.5	10.3	9.9	14.0	16.5	18.8	25.9	27.4	28.6
	Rainfall (mm)	19.9	23.5	145.5	88.0	166.9	68.8	53.7	77.3	18.2	0.0	0.0	0.0
Korakochori	Mean T (C)	24.6	20.6	17.0	12.2	10.0	9.3	13.3	15.8	18.7	25.4	26.9	27.9
	Rainfall (mm)	29.6	20.4	170.4	82.4	217.2	78.9	46.4	83.4	21.2	0.6	15.0	0.0
		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Origin	Parameter	2019–2020											
Pyrgos	Mean T (C)	25.0	21.1	17.7	13.3	10.4	12.2	14.0	16.0	21.2	23.2	27.5	28.1
	Rainfall (mm)	61.0	84.8	399.0	312.2	122.8	39.2	53.4	8.0	5.2	0.0	0.0	0.0
Kyparissia	Mean T (C)	25.2	21.7	17.9	13.3	10.9	12.4	14.3	15.9	21.4	23.6	27.7	28.4
	Rainfall (mm)	66.4	72.2	381.9	286.6	133.5	34.2	25.4	4.3	2.2	0.0	0.0	0.0
Korakochori	Mean T (C)	24.6	21.4	17.4	13.2	10.9	12.2	14.1	15.5	20.8	22.9	26.9	28.0
	Rainfall (mm)	53.2	94.8	402.3	298.2	136.5	40.8	51.7	11.9	21.8	0.0	0.0	0.0

[a]Mean T, mean temperature.

Table 2. Information regarding herbicides applied in each site.

Active ingredient	Abbreviation	Application rate	Sites where herbicide was applied	Trade name	Manufacturer
		g ai/ae ha^{-1}			
Glyphosate[a]	GLY	720/ 720/ 1,800	Citrus orchard/ olive grove/ vineyard	Meteor® TF 36 SL	Alfa Agricultural Supplies S.A., Hellas, Athens, Greece; https://www.alfagro.gr/
Pelargonic acid	PA	1,088	Citrus orchard/ olive grove/ vineyard	Beloukha ®	BASF Hellas S.A., Hellas, Athens, Greece; https://www.agro.basf.gr/el/
Flazasulfuron	FLA	50	Citrus orchard/ olive grove	Katana	Hellafarm S.A., Hellas, Athens, Greece; https://agro.hellafarm.gr/index.php
Oxyfluorfen	OXY	144	Citrus orchard/ olive grove	Fenfen 24 EC	Hellafarm S.A., Hellas, Athens, Greece; https://agro.hellafarm.gr/index.php
Flumioxazin	FMZ	150	Citrus orchard/ olive grove	Pledge 50 WP	Hellafarm S.A., Hellas, Athens, Greece; https://agro.hellafarm.gr/index.php
Penoxsulam + florasulam	PNX + FRM	15 + 7.5	Olive grove	Symbol™ 22.5 SC	Elanco Hellas S.A., Hellas, Athens, Greece; https://www.elanco.gr/
Cycloxydim	CXD	200	Vineyard	Focus® 10 EC	BASF Hellas S.A., Hellas, Athens, Greece; https://www.agro.basf.gr/el/
Quizalofop-*p*-ethyl	QZP	150	Vineyard	Jaguar® 5 EC	Alfa Agricultural Supplies S.A., Hellas, Athens, Greece; https://www.alfagro.gr/
Propaquizafop	PRF	150	Vineyard	Agil® 5 EC	Alfa Agricultural Supplies S.A., Hellas, Athens, Greece; https://www.alfagro.gr/

[a]Glyphosate was applied at 720 g ae ha^{-1} in the citrus orchard and the olive grove. The herbicide was applied at the rate of 1,800 g ae ha^{-1} in the vineyard due to the presence of *Sorghum halepense*.

residue management, and an untreated control. Glyphosate was applied once at 720 g ae ha^{-1}. Weeds were treated twice with pelargonic acid in a 15-d interval. Both pelargonic acid applications were carried out at an application rate of 1,088 g ha^{-1}. The application timings of the single mowing treatment, the second pelargonic acid application, and the glyphosate application were the same (Table 3). These treatments were applied when the weeds were between the 4- and 6-leaf growth stages. Flazasulfuron, oxyfluorfen, and flumioxazin were applied as preemergence herbicides at 50, 144, and 150 g ha^{-1}, respectively. Rainfall events occurred 2 d after treatment in April 2019. Precipitation of 26.8 mm was sufficient to ensure herbicide incorporation. For this purpose, plots were sprinkler-irrigated in April 2020. Water volume of 25 mm was applied to wet the top 15 cm of soil to activate herbicides. Glyphosate and flazasulfuron were applied at 200 kPa. Pelargonic acid, oxyfluorfen, and flumioxazin were applied at 250 kPa. Plot size was 7.5-m long by 7.5-m wide to include four trees per plot. A border of 1.5 m was kept between adjacent plots. In the second experimental year (2019 to 2020), new plots were established in this site to assure that the experiment was repeated in time.

In the olive grove, An RCBD was implemented with nine treatments assigned in four blocks. Treatments were: glyphosate, pelargonic acid (2x), flazasulfuron, oxyfluorfen, flumioxazin, penoxsulam + florasulam, barley residue management, white

Table 3. Dates of key field activities carried out at each site for each experimental year (2018–2019 and 2019–2020).

	Field					
	Citrus orchard		Olive grove		Vineyard	
Key activities[a]	2018–2019	2019–2020	2018–2019	2019–2020	2018–2019	2019–2020
CC sowing	October 2	October 4	October 1	October 3	October 3	October 5
CC termination	April 16	April 19	April 5	April 3	April 18	April 21
Glyphosate	May 17	May 19	April 30	April 3	May 18	May 20
Pelargonic acid	May 1 and 17	May 4 and 19	April 15 and 30	April 19 and May 3	May 2 and 18	May 5 and 20
Mowing	May 17	May 19	—	—	May 2 and 18	May 5 and 20
Preemergence herbicides	April 17	April 21	April 1	April 4	—	—
acetyl-CoA carboxylase inhibitors	—	—	—	—	18 May	20 May
NDVI evaluation	June 6 and 27	June 9 and 28	May 22 and June 14	May 24 and June 15	June 8 and 30	June 10 and July 2
Weed harvest	June 7 and 28	June 10 and 29	May 23 and June 15	May 24 and June 16	June 9 and July 1	June 11 and July 3
Crop harvest	October 6	October 7	November 17	November 17	September 21	September 16

[a]CC, cover crop; NDVI, normalized difference vegetation index.

mustard residue management, and an untreated control. Glyphosate was applied as a single treatment at 720 g ae ha^{-1}. Pelargonic acid was applied twice at 1,088 g ai ha^{-1} at 2-wk intervals. The application timings of the second pelargonic acid application and the single glyphosate application were the same (Table 3). These treatments were applied when the weeds had either small-sized (7- to 9-cm diameter) or large-sized rosettes (12- to 16-cm diameter). Preemergence herbicides included flazasulfuron (50 g ha^{-1}), oxyfluorfen (144 g ha^{-1}), flumioxazin (150 g ha^{-1}), and the application of a prepackage mixture of penoxsulam + florasulam at 15 + 7.5 g ha^{-1}. Herbicides were activated with 28.2 mm of water deposited on the soil surface during a single rain event in April 2019, 3 d after treatment. For the same reason, 13 mm of water was applied with sprinklers in April 2020 to incorporate herbicides. Application pressures for glyphosate, pelargonic acid, flazasulfuron, oxyfluorfen, and flumioxazin were the same as in the citrus orchard. Penoxsulam + florasulam mixture was applied at 250 kPa. Plots were 8-m long by 8-m wide. A 2-m border was kept between plots. In 2019 to 2020, the experiment was repeated in new plots in this site to repeat the experiment in time.

An RCBD was established in the vineyard with nine treatments repeated four times. Treatments were: glyphosate, pelargonic acid (2x), cycloxydim, quizalofop-*p*-ethyl, propaquizafop, mowing (two times), barley's residue management, white mustard residue management, and an untreated control. Glyphosate was applied once at 1,800 g ae ha^{-1}. Pelargonic acid was applied twice (1,088 g ha^{-1}) at 2-wk intervals. Cycloxydim, quizalofop-*p*-ethyl, and propaquizafop were applied once at 200, 150, and 150 g ha^{-1}, respectively. Two mowing operations were carried out in a 2-wk interval. The application timings of the second mowing treatment, the second pelargonic acid application, and the single applications of the other herbicides were the same (Table 3). These treatments were applied when the weeds were between the 4- and 6- leaf growth stages (30- to 40-cm height). Herbicides were applied at 200 kPa. Plot size was 4.5-m long by 3.5-m wide to include eight vines per plot. A border of 0.9 m was kept among neighboring rows. Borders among plots were 0.4 m. New plots were established in a new area in the vineyard in 2019 to 2020 to repeat the experiment in time.

Data Collection

For all trials, four 1-m^2 quadrats were placed in each plot. Normalized difference vegetation index (NDVI) and weed dry weight were measured from two quadrats in the first evaluation (Eval 1) and from the remaining two quadrats in the second evaluation (Eval 2). For NDVI measurements, the sensor was held stable at approximately 25 cm above the weed canopy for 5 seconds (Kong et al. 2009). A hand-held Trimble® GreenSeeker® (Trimble Agriculture Division, Westminster, CO, USA) sensor was used. The sensor unit has self-contained illumination in both red and near-infrared (NIR) bands and measures reflectance in the red and NIR regions of the electromagnetic spectrum (Tremblay et al. 2009) according to Equation 1:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \qquad [1]$$

For weed dry weight evaluations, weeds were harvested at a height of 5 cm with scissors. The samples were classified by weed species and oven-dried (DHG-9025, Knowledge Research S.A., Athens, Greece) at 65 C for 48 h to measure weed biomass. Data of the dry weight of the dominant species and total weed dry weight are presented for the citrus orchard. For the olive grove and the vineyard, only the dry weights of the dominant species are presented. *Conyza bonariensis* and *S. halepense* were the dominant species at these sites, contributing more than 90% of the total weed biomass (data not shown). For all trials, cover crop samples were also harvested from two 0.25-m^2 areas in each plot the day before termination. The samples were oven-dried and weighed to get an estimate of biomass production for both species.

The first evaluations (Eval 1) of NDVI and weed dry weight were carried out at fruit set (BBCH 71, 69, and 71 for the citrus trees, the olive trees, and the vines, respectively). The second evaluations (Eval 2) were conducted during the rapid growth stage of the produced fruits/grapes (BBCH 71 for the citrus trees, 71 to 75 for the olive trees and the vines). At these crucial growth stages, water stress and nutrient deficiencies can affect the number and size of the produced fruits/grapes, thus affecting the final yield of these crops more than stress conditions at later growth stages (García-Tejero 2011; Gómez-del-Campo 2014; Wenter et al. 2018).

Crops were harvested at fruit/grape maturity stage. In the citrus orchard, fruits were cut with scissors and measured per tree, and fruit yield per tree was estimated after fruit weight was measured (Bassal 2009). In the olive grove, fruits were harvested electromechanically and fruit weight per tree and per plot was measured (Bourazanis et al. 2016). In the vineyard, all clusters from each

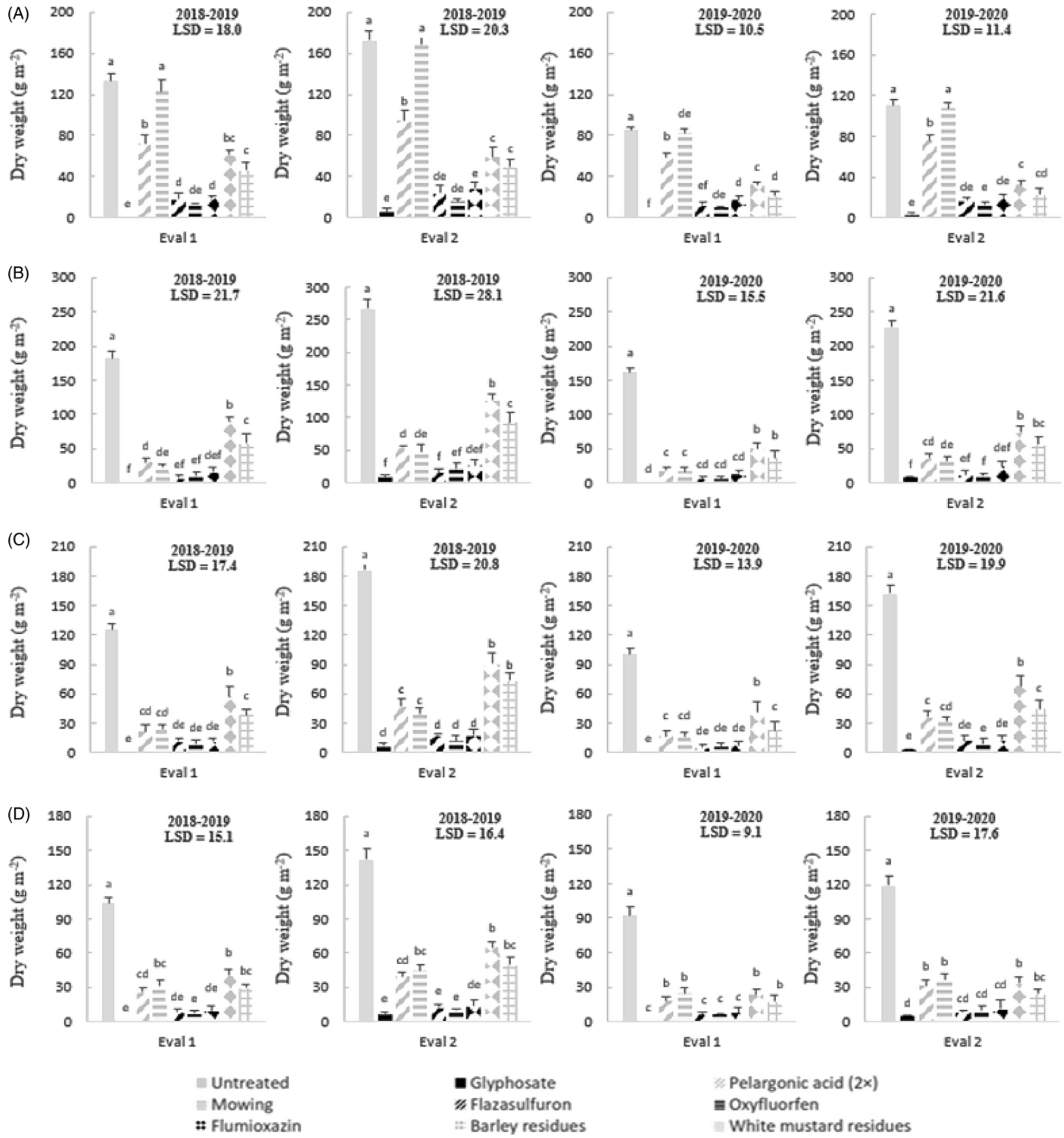

Figure 1. Dry weight (g m^{-2}) of (A) *Echinochloa crus-galli*, (B) *Chenopodium album*, (C) *Solanum nigrum*, and (D) *Amaranthus retroflexus* as recorded in the first (Eval 1) and second evaluations (Eval 2) of 2018–2019 and 2019–2020. For each evaluation, means were compared between treatments according to Fisher's LSD test at $\alpha = 0.05$ significance level (vertical bars indicate the standard errors of the measurements).

plot's vines were harvested and counted. μean berry weight was also measured to estimate grape yield per vine (Taskos et al. 2019). The final fruit/grape yield values per tree/vine are presented. Exact dates for crop harvest, weed biomass, and NDVI data collection are shown in Table 3. To protect crops from insect pests and fungal infections, the mandatory spraying programs had been implemented according to the special needs of each crop.

Statistical Analysis

Data from each evaluation were subjected to an initial two-way ANOVA. Treatments, years, and their interactions were considered as fixed effects, while blocks were considered random effects. When years affected the studied parameters ($P \leq 0.05$), data were analyzed to compare means between treatments in each separate year. All analyses were performed at $\alpha = 0.05$ significance level using STATGRAPHICS Centurion XVI (Statgraphics Technologies Inc., The Plains, VA, USA). Mean comparisons were performed according to Fisher's LSD test.

Weed dry weight was correlated with NDVI according to the linear model:

$$Y = A + B * X \quad [2]$$

where Y represents the values of weed dry weight, X represents NDVI values, A represents the intercept of the regression, and B represents the slope of the regression. These correlations were carried out between data obtained in the first (Eval 1) and second evaluations (Eval 2) in each year. For each separate year, crop yield was also correlated with weed dry weight values that were recorded in the second evaluation (Eval 2) according to the linear model (Equation 2). For the citrus orchard, total weed dry weight data (as recorded in Eval 2 of each separate year) were used to conduct the correlations. As for the other fields, the dry weight of the dominant species (as recorded in Eval 2 of each separate year) was used to conduct the correlations.

Results and Discussion

Weed Control in the Citrus Orchard

The effects of treatments and years on the dry weight of dominant weeds in the citrus orchard were significant ($P \leq 0.05$; Supplementary Table S1). The effects of year on weed dry weight were significant for all the dominant species ($P \leq 0.05$). Therefore, data were analyzed separately for 2018 to 2019 and 2019 to 2020 to separate the means between treatments in each year. This was carried out for every species mentioned.

Glyphosate application resulted in the lowest values of *E. crus-galli* dry weight in both evaluations and years. In both evaluations of 2018 to 2019 and 2019 to 2020, lower values of *E. crus-galli* dry weight corresponded to preemergence herbicide applications compared with cover crop residues, pelargonic acid, and mowing treatments (Figure 1A). Flazasulfuron, oxyfluorfen, and flumioxazin can effectively control summer annual grasses such as *E. crus-galli* that are common in fruit orchards (Plaza et al. 2021; Seale et al. 2020). Barley and white mustard residues suppressed *E. crus-galli* more than pelargonic acid and mowing in the first (Eval 1) and second evaluations (Eval 2) of both years. Similar results have been reported by Kruidhof et al. (2009). In addition, barley residues have been reported to effectively suppress *E. crus-galli* in Greece (Dhima et al. 2006). Pelargonic acid (two times) was characterized by lower efficacy on *E. crus-galli*. This result agrees with the findings of Travlos et al. (2020b), who reported low efficacy of pelargonic acid on grass weeds. Mowing did not reduce *E. crus-galli* biomass compared with the untreated in both years and evaluations. This can be attributed to the increased regrowth ability of this species after clipping (Butler et al. 2013).

As for *C. album*, the double pelargonic acid application reduced its dry weight compared with barley residues and the untreated in both evaluations of 2018 to 2019 and 2019 to 2020 (Figure 1B). The efficacy of pelargonic acid on broadleaf weeds has recently been recently highlighted (Travlos et al. 2020b). Mowing reduced *C. album* dry weight compared with cover crop residues and the untreated in both years and evaluations. Mowing can provide solutions in the control of annual broadleaf weeds in fruit orchards (Mia et al. 2020). Barley and white mustard residues also showed some suppressive ability on this species, especially in 2019 to 2020. These results are partially consistent with another study in which oat (*Avena sativa* L.) and canola (*Brassica napus* L.) residues reduced *C. album* emergence (Campiglia et al. 2012; Radicetti et al. 2013). Glyphosate and preemergence herbicides resulted in the lowest *C. album* biomass. In the second evaluations of both years, the performance of preemergence herbicides was comparable with that of glyphosate. These results agree with those of other studies in which flazasulfuron, oxyfluorfen, and flumioxazin provided sufficient control of *C. album* under European soil and climatic conditions (Jursík et al. 2011; Pacanoski et al. (2020).

In the first evaluation (Eval 1) of 2018 to 2019, preemergence herbicide application resulted in similar *S. nigrum* biomass compared with the double pelargonic acid application and the single mowing treatment. In the second evaluation (Eval 2), flazasulfuron, oxyfluorfen, and flumioxazin resulted in lower *S. nigrum* biomass than pelargonic acid (two times) and mowing (Figure 1C). These results suggest that although weeds can escape mechanical weed control operations or postemergence herbicide applications, the soil residual activity of preemergence herbicides enables the long-term management of weeds with an extended emergence window in fruit orchards (Ribeiro et al. 2021). In the second evaluation of 2019 to 2020, oxyfluorfen and glyphosate applications resulted in the lowest values of *S. nigrum* biomass. These findings are in line with other studies highlighting oxyfluorfen efficacy on *S. nigrum* and other weeds belonging to *Solanum* spp. (Liang et al. 2014). As for cover crops, their residues reduced weed dry weight compared with the untreated in both years and evaluations. This outcome is partially consistent with Campiglia et al.'s (2012) observation of the suppressive ability of barley residues on *S. nigrum*. Oat and canola residues were also reported to suppress *S. nigrum* (Radicetti et al. 2013).

Mowing, pelargonic acid (two times), and cover crop residues resulted in similar *A. retroflexus* biomass values, as observed in the first evaluation (Eval 1) of 2018 to 2019. Similar values corresponded to pelargonic acid (two times), mowing, and white mustard residues in the second evaluation (Eval 2). These treatments reduced *A. retroflexus* dry weight compared with the untreated (Figure 1D). Similar observations were made in 2019 to 2020. The satisfactory performance of mowing is in line with the recommendations of Donald (2006) that timely mowing operations can be highly effective on annual broadleaf species. The low biomass values recorded for *A. retroflexus* after pelargonic acid applications (two times) agree with Muñoz et al. (2020). Preemergence herbicides and glyphosate resulted in the lowest dry weight values for this species in both years and evaluations. Flazasulfuron, oxyfluorfen, and flumioxazin were reported in previous studies to control *A. retroflexus* and other weeds belonging to *Amaranthus* spp. (Mahoney et al. 2014; Ronchi and Silva 2004). Moreover, white mustard residue efficacy on *A. retroflexus* was comparable to that of preemergence herbicides in the second evaluation of 2019 to 2020. The suppressive effects of white mustard residues on *A. retroflexus* growth were also observed in a previous study by Alcántara et al. (2011) conducted in perennial orchards.

Both NDVI and total weed dry weight were affected by treatments and years ($P \leq 0.001$; Supplementary Table S2) in their first (Eval 1) and second evaluations (Eval 2), as shown by the two-way ANOVAs that were conducted. Because the effects of years on the studied parameters were significant, data for each evaluation were analyzed separately to separate means between treatments in each year.

Total weed dry weight was positively correlated with NDVI in the first evaluation (Eval 1) of 2018 to 2019 ($P \leq 0.001$; $n = 36$;

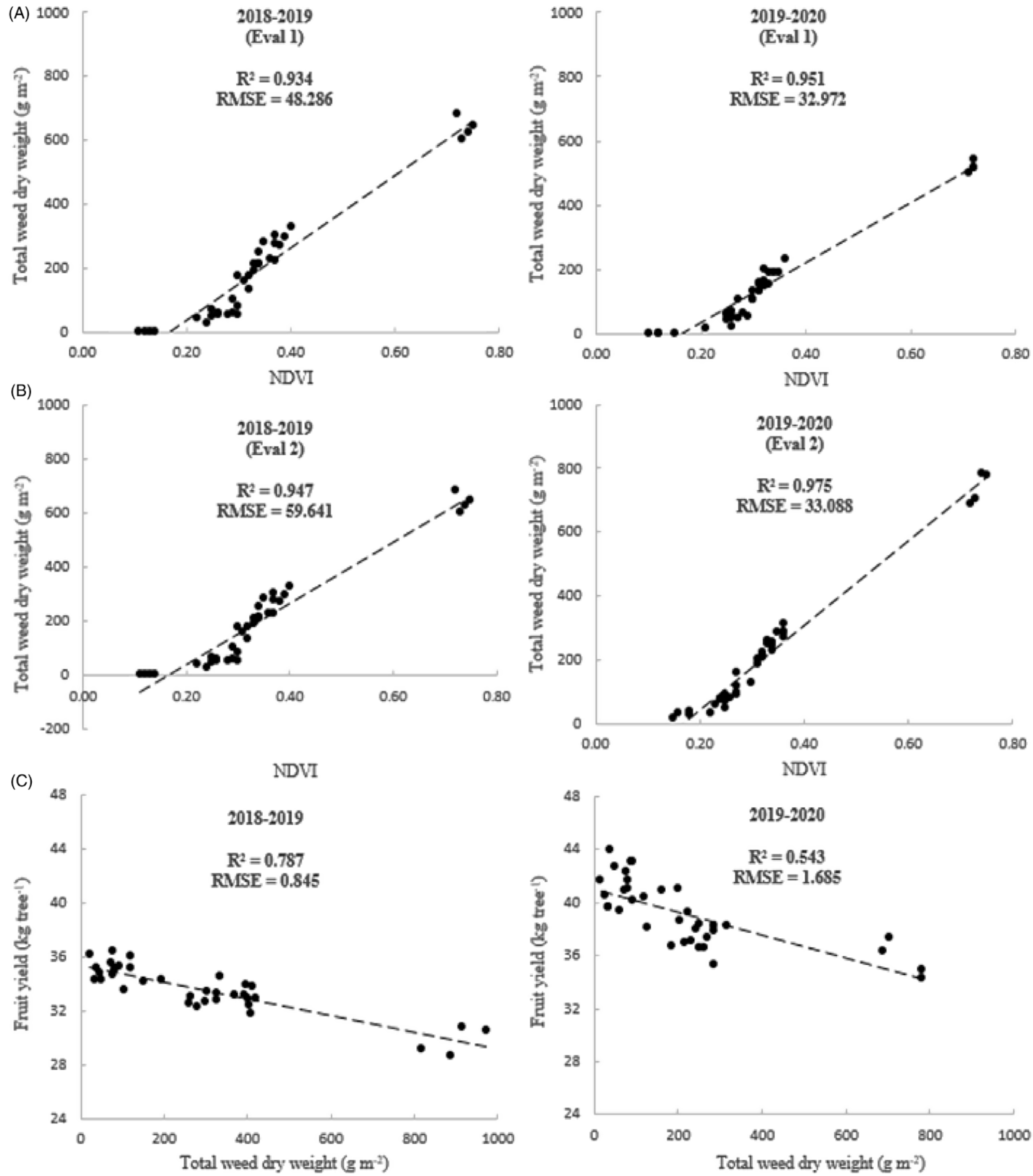

Figure 2. Linear regression analyses between (A) total weed dry weight (g m^{-2}) and normalized difference vegetation index (NDVI) in the first evaluation (Eval 1) of 2018–2019 and 2019–2020; (B) total weed dry weight (g m^{-2}) and NDVI in the second evaluation (Eval 2) of 2018–2019 and 2019–2020; and (C) fruit yield (kg $tree^{-1}$) and total weed dry weight (g m^{-2}) in 2018–2019 and 2019–2020. For the two correlations presented in C, total weed dry weight data are derived from the second evaluation (Eval 2) of each separate year. RMSE, root mean-square error.

$Y = -189.06 + 1{,}131.98 * X$; R = 0.966; $R^2 = 0.934$; RMSE [root mean-square error] = 48.286; Figure 2A) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = -153.859 + 930.565 * X$; R = 0.975; $R^2 = 0.951$; RMSE = 32.972; Figure 2A). The strong and positive correlation between total weed dry weight and NDVI was also obvious in the second evaluation (Eval 2) of 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = -285.012 + 1{,}590.43 * X$; R = 0.973; $R^2 = 0.947$; RMSE = 59.641; Figure 2B) and 2019 to 2020

Table 4. Normalized difference vegetation index (NDVI), total weed dry weight (g m^{-2}) in the first (Eval 1) and second evaluations (Eval 2) of 2018–2019 and 2019–2020 in the citrus orchard with fruit yield (kg $tree^{-1}$) data also presented as recorded in 2018–2019 and 2019–2020.[a]

	2018–2019				
	NDVI		Total weed dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Fruit yield
			g m^{-2}		kg $tree^{-1}$
Untreated	0.735 a	0.763 a	638.2 a	899.2 a	29.754 c
Glyphosate	0.125 e	0.193 e	0.0 f	36.6 f	35.086 a
Pelargonic acid (two times)	0.323 c	0.340 c	189.1 d	262.5 d	33.176 b
Mowing	0.353 bc	0.370 c	250.1 c	372.3 bc	32.984 b
Flazasulfuron	0.273 d	0.285 d	62.5 e	98.6 e	35.038 a
Oxyfluorfen	0.260 d	0.275 d	52.7 e	87.2 ef	34.983 a
Flumioxazin	0.283 d	0.283 d	79.1 e	124.5 e	34.867 a
Barley residues	0.380 b	0.403 b	294.3 b	407. b	32.909 b
White mustard residues	0.350 bc	0.368 c	213.3 cd	328.3 cd	33.071 b
LSD	0.032	0.031	39.7	59.6	1.267
P-value	***	***	***	***	***
	2019–2020				
	NDVI		Total weed dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Fruit yield
			g m^{-2}		kg $tree^{-1}$
Untreated	0.718 a	0.735 a	516.3 a	739.1 a	35.711 c
Glyphosate	0.123 g	0.168 e	0.0 e	28.3 e	41.428 a
Pelargonic acid (two times)	0.310 cd	0.323 c	143.2 c	200.1 bc	37.787 b
Mowing	0.330 bc	0.348 b	183.3 b	236.7 b	37.648 b
Flazasulfuron	0.265 ef	0.255 d	44.2 d	74.4 de	41.329 a
Oxyfluorfen	0.245 f	0.243 d	45.5 d	69.3 de	41.304 a
Flumioxazin	0.275 e	0.260 d	72.1 d	109.8 d	41.183 a
Barley residues	0.335 b	0.350 b	180.8 b	264.8 b	37.689 b
White mustard residues	0.300 d	0.318 c	127.3 c	192.7 c	37.955 b
LSD	0.025	0.021	33.5	53.4	1.960
P-value	***	***	***	***	***

[a]For each evaluation, mean separation was conducted according to Fisher's LSD test. P-values are shown as derived from ANOVA conducted for each growing season at $\alpha = 0.05$ probability level. Different letters in the same column indicate significant differences among treatments for each evaluation conducted in each separate growing season.
***$P \leq 0.001$.

($P \leq 0.001$; $n = 36$; $Y = -218.929 + 1{,}318.02 * X$; R = 0.987; $R^2 = 0.975$; RMSE = 33.088; Figure 2B). These correlations indicate that NDVI can be a reliable, nondestructive tool for weed control evaluation and agree with previous findings (Travlos et al. 2021).

In both years and evaluations, glyphosate and preemergence herbicides resulted in lower values of NDVI and total weed dry weight compared with other treatments (Table 4). In the second evaluation of 2018 to 2019, oxyfluorfen performance was comparable to that of glyphosate. Flazasulfuron and oxyfluorfen performances were comparable to that of glyphosate in the second evaluation of 2019 to 2020. The efficacy of preemergence herbicides is encouraging in a time when glyphosate resistance is a growing problem in the perennial orchards of the Mediterranean region (Tahmasebi et al. 2018; Travlos et al 2020a; Vazquez-Garcia et al. 2020).

Pelargonic acid (two times) reduced NDVI and total weed dry weight compared with barley residues and the untreated in the first and second evaluations of 2018 to 2019. Our findings indicate that repeated applications of pelargonic acid to small-sized weeds can provide solutions for weed control in fruit orchards (Young 2004). In the second evaluation of 2019 to 2020, white mustard residues reduced NDVI and total weed biomass compared with mowing. No significant differences were detected between barley residues, mowing, and pelargonic acid. The higher weed- suppression ability of both species can be attributed to the higher rainfall in the second growing season than in the first (Table 1). The higher rainfall in the winter of 2019 to 2020 resulted in higher biomass production in both species (data not shown) and consequently higher weed suppression. These results agree with those of MacLaren et al. (2019). Our findings indicate also that mowing and cover crop residue management cannot achieve sufficient weed control as single treatments. However, these practices can contribute to weed management in perennial orchards, especially when combined with the applications of glyphosate or alternative herbicides (Alcántara et al. 2011; Mia et al. 2020; Raimondi et al. 2020).

Fruit yield was also affected by treatments and years ($P \leq 0.001$; Supplementary Table S2), as shown in the results of the initial two-way ANOVA. The significantly higher fruit yield per tree in the second growing season is mainly attributed to the phenomenon of alternate bearing exhibited by the citrus trees (Bassal 2009). Because years affected fruit yield, data were analyzed separately for each year to compare means among treatments in each year.

In 2018 to 2019, glyphosate, flazasulfuron, oxyfluorfen, and flumioxazin resulted in the highest fruit yields per tree. Intermediate fruit yield values corresponded to pelargonic acid (two times), mowing, and barley residues and white mustard residues; the lowest yields were recorded in the untreated plots. The same observations were made in 2019 to 2020. The highest fruit yields in plots treated with glyphosate and preemergence herbicides are attributed to the higher levels of weed control provided by these treatments. This is further supported by the negative correlations obtained between fruit yield and total weed dry weight in both 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = 35.387 - 0.00627696 * X$; $R = -0.887$; $R^2 = 0.787$; RMSE = 0.845; Figure 2C) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = 41.0395 - 0.00874668 * X$; $R = -0.737$; $R^2 = 0.543$; RMSE = 1.675; Figure 2C). These results are consistent with those of Merwin and Ray (1997), who observed 62% yield loss due to weed interference in a newly planted fruit orchard. In addition, our findings suggest that weed competition can be an important obstacle limiting citrus crops' productivity under Mediterranean soil and climatic conditions, as also mentioned by Onen et al. (2018).

Weed Control in the Olive Grove

NDVI and *C. bonariensis* dry weight were affected by treatments and years in both their first and second evaluations ($P \leq 0.001$; Supplementary Table S3) given the results of the two-way ANOVAs that were conducted. Because the effects of years on both parameters were significant, data for each evaluation were analyzed separately for each experimental year.

Conyza bonariensis dry weight was positively correlated with NDVI in the first evaluation (Eval 1) of 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = -182.396 + 833.892 * X$; $R = 0.901641$; $R^2 = 0.812$; RMSE = 72.446; Figure 3A) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = -158.547 + 727.451 * X$; $R = 0.901$; $R^2 = 0.812$; RMSE = 63.764; Figure 3A). The correlation between *C. bonariensis* biomass and NDVI was strong and positive in the second evaluation (Eval 2) of 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = -203.347 + 910.336 * X$; $R = 0.894$; $R^2 = 0.799$; RMSE = 82.823; Figure 3B) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = -166.913 + 769.842 * X$; $R = 0.908$; $R^2 = 0.825$; RMSE = 64.731; Figure 3B). These results suggest that NDVI values were in accordance with those of weed biomass and agree with other studies in which this vegetation index was effectively used to estimate herbicide efficacy (Lewis et al. 2014; Travlos et al. 2021).

In both years and evaluations, the lowest NDVI and *C. bonariensis* dry weight values were recorded in plots treated with glyphosate (Table 5). These results highlight the role of glyphosate in the control of this noxious species, which can cause severe yield losses in important perennial crops (Bajwa et al. 2016; Curt et al. 2017). Flazasulfuron resulted in lower NDVI and *C. bonariensis* biomass than oxyfluorfen, penoxsulam + florasulam, and flumioxazin. These results were common in both evaluations of 2018 to 2019 and 2019 to 2020 and highlight the potential of flazasulfuron as an alternative herbicide for *C. bonariensis* control and are consistent with those of another recent study (Tahmasebi et al. 2018). The same authors also reported that flazasulfuron was more effective on *C. bonariensis* compared with oxyfluorfen and flumioxazin, as also observed in the present study. Penoxsulam + florasulam reduced NDVI and *C. bonariensis* biomass compared with flumioxazin. This was observed in the first (Eval 1) and second evaluations (Eval 2) of 2018 to 2019 and validated in the corresponding evaluations of 2019 to 2020. The higher efficacy of the prepackaged triazolopyrimidine mixture on *C. bonariensis* compared with flumioxazin was reported in previous studies conducted in olive groves in western Greece (Travlos et al. 2014).

Pelargonic acid (two times) did not cause noticeable reductions in weed biomass in all the evaluations carried out in the olive grove, in contrast to the results obtained in the citrus orchard. This difference between sites can be attributed to the presence of *C. bonariensis* as the dominant species in the olive grove. The presence of buds in the *C. bonariensis* taproot enable the rapid regrowth of this species after clipping (Wu 2007). Regarding cover crop residues, they caused some reductions in NDVI and weed biomass compared with pelargonic acid and the untreated. These results were recorded in 2018 to 2019 and confirmed in 2019 to 2020. Recent studies reported *C. bonariensis* suppression after mulching with the residues of winter-grown cereal and cruciferous cover crops (Cholette et al. 2018; Pittman et al. 2019). In these studies, cover crop residues suppressed *C. bonariensis* in the short time after cover crop termination, and then weeds were suppressed in the subsequent cash crops. Because this is not possible in perennial orchards, supplementary glyphosate applications are required to control this species later in the growing season. However, integrated weed management systems including combinations of cultural practices and alternative herbicides should be further evaluated for the management of this species. This is further supported by glyphosate-resistance cases reported for *C. bonariensis* accessions in the perennial crops of the Mediterranean region (Amaro-Blanco et al. 2018; Tahmasebi et al. 2018; Travlos and Chachalis 2010).

The results of the two-way ANOVA indicated that treatments and years influenced fruit yield per tree at a significant point ($P \leq 0.001$; Supplementary Table S3). Because the effects of years on fruit yield per tree were significant, yield data were analyzed separately for the first and second experimental years to separate means among treatments in each year. Olive trees were in the high-yield year of their alternate bearing cycle, and this mainly explains the higher yields of 2018 to 2019 (Bourazanis et al. 2016).

In 2018 to 2019, glyphosate resulted in the highest fruit yield. Flazasulfuron, penoxsulam + florasulam, oxyfluorfen, and white mustard residues increased fruit yield compared with pelargonic acid (two times), flumioxazin, and barley residues (Table 5). In 2019 to 2020, glyphosate and flazasulfuron provided the highest yields. The yield values that corresponded to penoxsulam + florasulam, oxyfluorfen, and white mustard residues were close to the value that corresponded to flazasulfuron. Pelargonic acid (two times), flumioxazin, and barley residues resulted in lower fruit yield. The lowest yield values were recorded in the untreated plots in both years. These results trend with other studies in which *C. bonariensis* control was essential to avoid severe yield losses in perennial crops (Curt et al. 2017). The effects of *C. bonariensis* competition on the productivity of the olive trees is further validated by the strong and negative correlations obtained between fruit yield per tree and *C. bonariensis* dry weight in 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = 15.0611 - 0.0065342 * X$; $R = -0.953$; $R^2 = 0.909$; RMSE = 0.380; Figure 3C) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = 9.82386 - 0.0074612 * X$; $R = -0.961$; $R^2 = 0.924$; RMSE = 0.330; Figure 3C).

Weed Control in the Vineyard

The effects of treatments and years on NDVI and *S. halepense* dry weight in both their first and second evaluations were significant ($P \leq 0.001$; Supplementary Table S4), as shown in the results of the two-way ANOVAs that were carried out to check whether data could be pooled across growing seasons. As a result, data of each

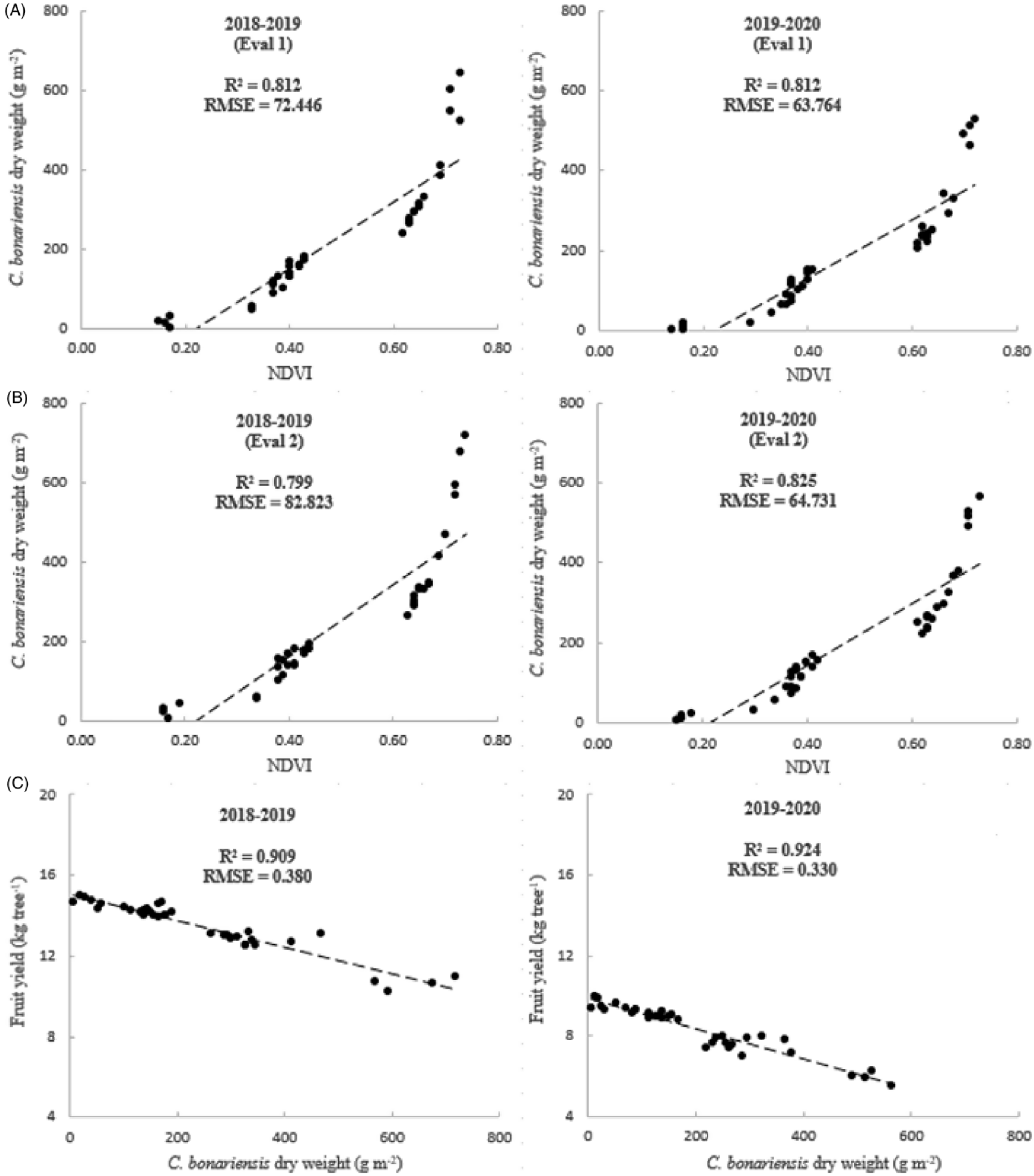

Figure 3. Linear regression analyses between (A) *Conyza bonariensis* dry weight (g m^{-2}) and normalized difference vegetation index (NDVI) in the first evaluation (Eval 1) of 2018–2019 and 2019–2020; (B) *Conyza bonariensis* dry weight (g m^{-2}) and NDVI in the second evaluation (Eval 2) of 2018–2019 and 2019–2020; and (C) fruit yield (kg $tree^{-1}$) and *Conyza bonariensis* dry weight (g m^{-2}) in 2018–2019 and 2019–2020. For the two correlations presented in C, weed dry weight data are derived from the second evaluation (Eval 2) of each separate year. RMSE, root mean-square error.

evaluation were analyzed to compare means between treatments in each experimental year.

Sorghum halepense dry weight correlations with NDVI were noticeable in the first evaluation (Eval 1) of 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = -293.29 + 1{,}324.79 * X$; $R = 0.982$; $R^2 = 0.966$; RMSE = 56.632; Figure 4A) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = -249.16 + 1{,}227.34 * X$; $R = 0.979$; $R^2 = 0.958$; RMSE = 59.421; Figure 4A). The correlations between

Table 5. Normalized difference vegetation index (NDVI) and *Conyza bonariensis* dry weight (g m^{-2}) in the first (Eval 1) and second evaluations (Eval 2) of 2018–2019 and 2019–2020 in the olive grove with fruit yield data (kg tree^{-1}) also presented as recorded in 2018–2019 and 2019–2020.[a]

	2018–2019				
	NDVI		*C. bonariensis* dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Fruit yield
			———g m^{-2}———		kg tree^{-1}
Untreated	0.720 a	0.723 a	576.4 a	639.3 a	10.655 d
Glyphosate	0.163 f	0.170 g	15.0 f	24.5 f	14.820 a
Pelargonic acid (two times)	0.670 b	0.683 b	353.4 b	392.3 b	12.757 c
Flazasulfuron	0.355 e	0.363 f	73.4 e	82.3 e	14.380 b
Oxyfluorfen	0.405 d	0.415 de	142.2 d	155.7 d	14.188 b
Flumioxazin	0.638 c	0.645 c	284.5 c	314.4 c	12.913 c
Penoxsulam + florasulam	0.413 d	0.420 d	152.7 d	160.3 d	14.184 b
Barley residues	0.633 c	0.643 c	271.6 c	298.0 c	12.902 c
White mustard residues	0.388 d	0.395 e	143.7 d	163.2 d	14.181 b
LSD	0.027	0.023	42.8	51.1	0.341
P-value	***	***	***	***	***
	2019–2020				
	NDVI		*C. bonariensis* dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Fruit yield
			———g m^{-2}———		kg tree^{-1}
Untreated	0.710 a	0.715 a	497.0 a	524.4 a	5.896 d
Glyphosate	0.155 g	0.163 f	8.9 f	14.8 f	9.659 a
Pelargonic acid (two times)	0.658 b	0.675 b	305.4 b	338.2 b	7.477 c
Flazasulfuron	0.338 f	0.348 e	49.4 e	59.9 e	9.317 ab
Oxyfluorfen	0.393 d	0.398 d	125.7 d	133.2 d	9.019 b
Flumioxazin	0.623 c	0.633 c	235.0 c	268.6 c	7.698 c
Penoxsulam + florasulam	0.388 de	0.393 d	119.8 d	130.2 d	9.021 b
Barley residues	0.625 c	0.630 c	224.6 c	238.0 c	7.623 c
White mustard residues	0.363 ef	0.373 de	98.8 d	118.2 d	9.088 b
LSD	0.026	0.026	34.0	34.7	0.364
P-value	***	***	***	***	***

[a]For each evaluation, mean separation was conducted according to Fisher's LSD test. P-values are shown as derived from ANOVA conducted for each growing season at α = 0.05 probability level. Different letters in the same column indicate significant differences between treatments for each evaluation conducted in each separate year.
***P ≤ 0.001.

S. halepense dry weight and NDVI were strong and positive in the second evaluation (Eval 2) of 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = -334{,}788 + 1{,}395.94 * X$; $R = 0.986$; $R^2 = 0.973$; RMSE = 53.286; Figure 4B) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = -264.444 + 1{,}283.92 * X$; $R = 0.977$; $R^2 = 0.955$; RMSE = 65.777; Figure 4B). In both years and evaluations, glyphosate, cycloxydim, quizalofop-*p*-ethyl, and propaquizafop resulted in the lowest NDVI and *S. halepense* dry weight values compared with mowing (two times), pelargonic acid (two times), barley residues, white mustard residues, and the untreated (Table 6). All the acetyl-CoA carboxylase inhibitors tested were as effective as glyphosate. The satisfactory performance of cycloxydim is consistent with the findings of Scarabel et al. (2014), who also observed excellent efficacy of this herbicide on *S. halepense*. The low NDVI and *S. halepense* dry weight values in plots treated with quizalofop-*p*-ethyl agree with Johnson et al. (2003). Propaquizafop achieved sufficient *S. halepense* control in the field trials of Haitas et al. (1995), as also observed in the current study.

Mowing (two times) and pelargonic acid (two times) caused slight reductions in *S. halepense* biomass compared with the untreated. No significant differences were detected in NDVI between these treatments. These results were common in the first (Eval 1) and the second evaluations (Eval 2) of 2018 to 2019 and 2019 to 2020. Mowing was more effective in the citrus orchard, where it controlled erect, annual broadleaf weeds. In contrast, the regrowth ability of *S. halepense* after clipping can explain the higher NDVI and weed biomass values recorded after mowing in the vineyard. It should be also noted that the poor performance of mowing for controlling grass weeds was similar in these two sites, given the regrowth ability of *S. halepense* and *E. crus-galli* after clipping (Butler et al. 2013; Horowitz 1972). Pelargonic acid was also much less effective in this field compared with the other field trials presented. Although this natural herbicide could control annual broadleaves in the citrus orchard and *C. bonariensis* individuals that were in very early growth stages in the olive grove (visual observations), *S. halepense* regrew rapidly after treatment in the vineyard. Another explanation for this difference among sites is that pelargonic acid is a contact-type herbicide that tends to be more effective on broadleaf weeds with increased leaf area compared with narrow-leaved grass species (Travlos et al. 2020b).

Barley and white mustard residues caused some reductions in NDVI and weed dry weight in comparison to the untreated, mowing (two times), and pelargonic acid (two times) treatments in both years and evaluations. Cover crop residue might have suppressed the emergence of *S. halepense* plants derived from seed, while these treatments could not suppress the emergence of *S. halepense* plants derived from rhizome. This can also explain the lower efficacy of cover crop residues in this site compared with sites dominated by annual species reproduced exclusively by seed (i.e., citrus orchard, olive grove). Regarding the effects of mulching on *S. halepense*, an interesting approach by Uremis et al. (2009) suggested that the residues of cover crops belonging to the botanical family of *Brassicaceae* can be incorporated into the soil to suppress rhizome growth. Further research is required to evaluate such practices for

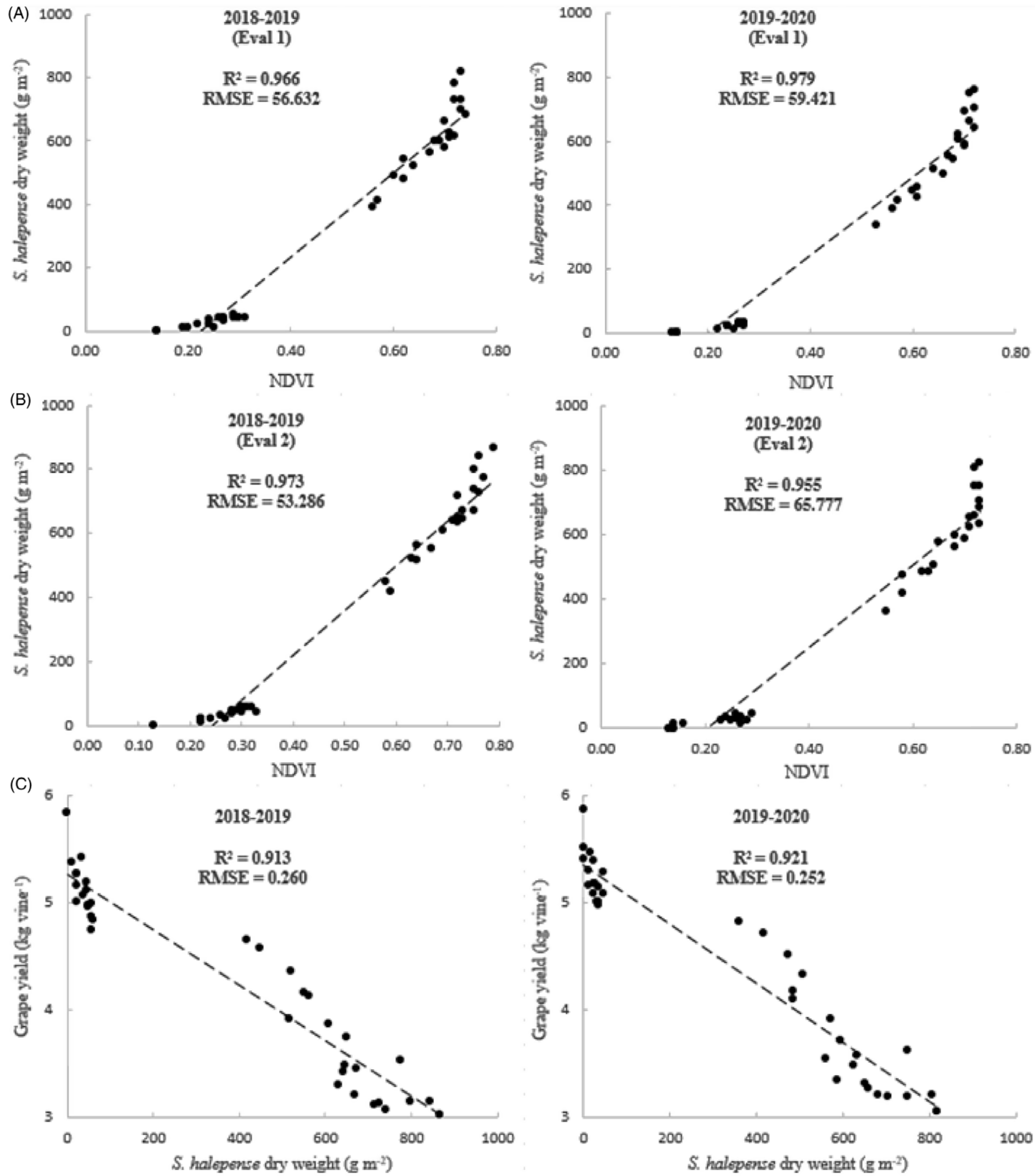

Figure 4. Linear regression analyses between (A) *Sorghum halepense* dry weight (g m^{-2}) and normalized difference vegetation index (NDVI) in the first evaluation (Eval 1) of 2018–2019 and 2019–2020; (B) *Sorghum halepense* dry weight (g m^{-2}) and NDVI in the second evaluation (Eval 2) of 2018–2019 and 2019–2020; and (C) fruit yield (kg $tree^{-1}$) and *Sorghum halepense* dry weight (g m^{-2}) in 2018–2019 and 2019–2020. For the two correlations presented in C, weed dry weight data are derived from the second evaluation (Eval 2) of each separate year. RMSE, root mean-square error.

S. halepense control under different soil and climatic conditions. This applies also for other nonchemical control methods such as mowing. Although two mowing passes were not effective in this site, repeated and frequent mowing controls *S. halepense* seedlings and reduces rhizome growth and shoot regrowth after clipping (Travlos et al. 2019; Warwick and Black 1983). For instance, mowing *S. halepense* at the ground surface every 2 wk from spring to autumn caused significant reductions on *S. halepense* dry weight

Table 6. Normalized difference vegetation index (NDVI) and *Sorghum halepense* dry weight (g m^{-2}) in the first (Eval 1) and second evaluations (Eval 2) of 2018–2019 and 2019–2020 in the vineyard with grape yield data (kg vine^{-1}) are also presented as recorded in 2018–2019 and 2019–2020.[a]

	2018–2019				
	NDVI		*S. halepense* dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Grape yield
			g m^{-2}		kg vine^{-1}
Untreated	0.725 a	0.768 a	755.9 a	805.6 a	3.195 e
Glyphosate	0.228 d	0.243 d	19.0 f	22.3 f	5.376 a
Pelargonic acid (two times)	0.720 a	0.740 a	671.6 b	721.8 b	3.219 e
Mowing (two times)	0.705 ab	0.730 ab	604.5 c	565.0 c	3.426 e
Cycloxydim	0.235 d	0.268 d	26.9 f	37.7 f	5.192 ab
Quizalofop-*p*-ethyl	0.258 d	0.278 d	32.9 f	43.9 f	5.007 b
Propaquizafop	0.258 d	0.280 d	34.8 f	44.1 f	4.966 b
Barley residues	0.653 b	0.678 b	541.1 d	579.3 d	3.843 d
White mustard residues	0.588 c	0.610 c	459.5 e	487.0 e	4.431 c
LSD	0.064	0.058	52.0	53.5	0.330
P-value	***	***	***	***	***
	2019–2020				
	NDVI		*S. halepense* dry weight		
Treatment	Eval 1	Eval 2	Eval 1	Eval 2	Grape yield
			g m^{-2}		kg vine^{-1}
Untreated	0.710 a	0.725 a	717.8 a	770.9 a	3.271 e
Glyphosate	0.200 d	0.205 d	8.2 f	9.1 f	5.487 a
Pelargonic acid (two times)	0.708 a	0.723 a	639.0 b	678.5 b	3.293 e
Mowing (two times)	0.685 ab	0.705 ab	574.7 c	616.3 c	3.487 e
Cycloxydim	0.208 d	0.220 d	13.6 f	18.1 f	5.296 ab
Quizalofop-*p*-ethyl	0.225 d	0.225 d	22.1 f	29.9 f	5.118 b
Propaquizafop	0.235 d	0.248 d	24.0 f	30.9 f	5.133 b
Barley residues	0.630 bc	0.650 bc	473.1 d	531.5 d	3.973 d
White mustard residues	0.565 c	0.583 c	396.9 e	433.1 e	4.560 c
LSD	0.066	0.068	43.2	48.7	0.298
P-value	***	***	***	***	***

[a]For each evaluation, mean separation was conducted according to Fisher's LSD test. P-values are shown as derived from ANOVA conducted for each growing season at $\alpha = 0.05$ probability level. Different letters in the same column indicate significant differences between treatments for each evaluation conducted in each separate year.
***$P \leq 0.001$.

and rhizome length in early studies (Horowitz 1972). The need to optimize integrated management systems to eradicate *S. halepense* is further supported by cases reporting the presence of *S. halepense* accessions with resistance to selective herbicides and glyphosate in the perennial orchards of the Mediterranean zone (Heap 2021; Vazquez-Garcia et al. 2020). To maintain efficacy over time, timely herbicide applications should be combined with cultural practices such as mowing (Travlos et al. 2019). Such systems have been reported to provide sufficient control of perennial rhizomatous weed species that are troublesome in perennial crops (Raimondi et al. 2020).

As for grape yield, it was also affected by treatments and years ($P \leq 0.001$; Supplementary Table S4), as shown in the results of the initial two-way ANOVA. Therefore, means were compared among treatments in each separate year. In 2018 to 2019, the highest grape yields were observed in plots treated with glyphosate and cycloxydim. Quizalofop-*p*-ethyl and propaquizafop applications led to grape yield values that were comparable to those with cycloxydim. Lower yields were recorded in plots mulched with cover crop residues. The lowest yields corresponded to mowing (two times), pelargonic acid (two times), and the untreated. These results were also observed in 2019 to 2020. The herbicide treatments that most reduced *S. halepense* dry weight resulted in the highest grape yields, as highlighted by the strong and negative correlations observed between grape yield per vine and *S. halepense* dry weight in both 2018 to 2019 ($P \leq 0.001$; $n = 36$; $Y = 5.27244 - 0.00258846 * X$; $R = -0.955846$; $R^2 = 0.913642$; RMSE = 0.260154; Figure 4C) and 2019 to 2020 ($P \leq 0.001$; $n = 36$; $Y = 5.35936 - 0.00276311 * X$; $R = -0.959$; $R^2 = 0.921$; RMSE = 0.252; Figure 4C). The significant effect of weed competition on grape yield was expected, because *S. halepense* is a troublesome species that can compete for water and nutrients and subsequently reduce crop productivity in vineyards (Travlos et al. 2018).

Acknowledgments. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors. No conflicts of interest have been declared.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2021.55

References

Alcántara C, Pujadas A, Saavedra M (2011) Management of *Sinapis alba* subsp. *mairei* winter cover crop residues for summer weed control in southern Spain. Crop Prot 30:1239–1244

Amaro-Blanco I, Fernández-Moreno, PT, Osuna-Ruiz, MD, Bastida F, De Prado R (2018) Mechanisms of glyphosate resistance and response to alternative herbicide-based management in populations of the three *Conyza* species introduced in southern Spain. Pest Manag Sci 74:1925–1937

Bajwa AA, Sadia S, Ali HH, Jabran K, Peerzada AM, Chauhan BS (2016) Biology and management of two important *Conyza* weeds: a global review. Environ Sci Pollut Res 23:24694–24710

Bassal MA (2009) Growth, yield and fruit quality of 'Marisol' clementine grown on four rootstocks in Egypt. Sci Hortic 119:132–137

Beckie HJ, Flower KC, Ashworth MB (2020) Farming without glyphosate? Plants 9:96

Bourazanis G, Roussos PA, Argyrokastritis I, Kosmas C, Kerkides P (2016) Evaluation of the use of treated municipal waste water on the yield, oil quality, free fatty acids' profile and nutrient levels in olive trees cv Koroneiki, in Greece. Agric Water Manag 163:1–8

Butler RA, Brouder, SM, Johnson, WG, Gibson KD (2013). Response of four summer annual weed species to mowing frequency and height. Weed Technol 27:798–802

Campiglia E, Radicetti E, Mancinelli R (2012) Weed control strategies and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. Crop Prot 33:65–73

Cholette TB, Soltani N, Hooker, DC, Robinson DE, Sikkema PH (2018) Suppression of glyphosate-resistant Canada fleabane (*Conyza canadensis*) in corn with cover crops seeded after wheat harvest the previous year. Weed Technol 32:244–250

Curt MD, Mauri PV, Sanz M, Cano-Ruiz J, Del Monte JP, Aguado PL, Sánchez J (2017) The ability of the *Arundo donax* crop to compete with weeds in central Spain over two growing cycles. Ind Crops Prod 108:86–94

Dhima KV, Vasilakoglou IB, Eleftherohorinos IG, Lithourgidis AS (2006) Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Sci 46:345–352

Didon UM, Kolseth AK, Widmark D, Persson P (2014) Cover crop residues—effects on germination and early growth of annual weeds. Weed Sci 62: 294–302

Donald WW (2006) Mowing for weed management. Pages 357–400 *in* Singh HP, Batish DR, Kohli KR, eds. Handbook of Sustainable Weed Management. Boca Raton, FL: CRC Press

Duke SO (2020) Glyphosate: environmental fate and impact. Weed Sci 68: 201–207

Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. Pest Manag Sci 64:319–325

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KH (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Till Res 117:172–183

Fogliatto S, Ferrero A, Vidotto F, Sparks D (2020) Current and future scenarios of glyphosate use in Europe: are there alternatives? Pages 219–278 *in* Sparks DL, ed. Advances in Agronomy. Volume 163. Cambridge: Academic Press

García-Tejero I, Durán-Zuazo VH, Arriaga-Sevilla J, Muriel-Fernández JL (2011) Impact of water stress on citrus yield. Agron Sustain Dev 32:651–659

Gerhards R, Schappert A (2020) Advancing cover cropping in temperate integrated weed management. Pest Manag Sci 76:42–46

Gómez-del-Campo M, Pérez-Expósito MÁ, Hammami SB, Centeno A, Rapoport HF (2014) Effect of varied summer deficit irrigation on components of olive fruit growth and development. Agric Water Manag 137:84–91

Haitas VC, Kotoula-Syka E., Eleftherohorinos IG (1995) Influence of propaquizafop application rate and time on *Sorghum halepense* (L.) Pers. control and cotton (*Gossypium hirsutum*) yield. Weed Res 35:1–6

Heap I (2021) The International Herbicide-Resistant Weed Database. http://weedscience.org/Home.aspx. Accessed: July 29, 2021

Horowitz M (1972) Effects of frequent clipping on three perennial weeds, *Cynodon dactylon* (L.) Pers., *Sorghum halepense* (L.) Pers. and *Cyperus rotundus* L. Exp Agric 8:225–234

Johnson WG, Li J, Wait JD (2003) Johnsongrass control, total nonstructural carbohydrates in rhizomes, and regrowth after application of herbicides used in herbicide-resistant corn (*Zea mays*). Weed Technol 17:36–41

Jursík M, Andr J, Holec J, Soukup J (2011) Efficacy and selectivity of post-emergent application of flumioxazin and oxyfluorfen in sunflower. Plant Soil Environ 57:532–539

Kong L, Si J, Feng B, Li S, Wang F, Sayre K (2009) Differential responses of two types of winter wheat (*Triticum aestivum* L.) to autumn-and spring-applied mesosulfuron-methyl. Crop Prot 28:387–392

Kruidhof HM, Bastiaans L, Kropff MJ (2009) Cover crop residue management for optimizing weed control. Plant Soil 318:169–184

Kudsk P, Mathiassen SK (2020) Pesticide regulation in the European Union and the glyphosate controversy. Weed Sci 68:214–222

Lewis D, Jeffries M, Gannon T, Richardson R, Yelverton F (2014) Persistence and bioavailability of aminocyclopyrachlor and clopyralid in turfgrass clippings: recycling clippings for additional weed control. Weed Sci 62: 493–500

Liang Y, Jia H, Dong X, Li J, Liu Y, Cao Z, Wang C, Yang D (2014) The effects of four soil-applied herbicides on control of *Solanum nigrum* L. and safety evaluation. Acta Agric Univ Jiangxi 36:102–108

Ligoxigakis EK, Vakalounakis DJ, Thanassoulopoulos CC (2002) Weed hosts of *Verticillium dahliae* in Crete: Susceptibility, symptomatology and significance. Phytoparasitica 30:511–518

MacLaren C, Swanepoel P, Bennett J, Wright J, Dehnen-Schmutz K (2019) Cover crop biomass production is more important than diversity for weed suppression. Crop Sci 59:733–748

Mahoney KJ, Shropshire C, Sikkema PH (2014) Weed management in conventional- and no-till soybean using flumioxazin/pyroxasulfone. Weed Technol 28:298–306

Merwin IA, Ray JA (1997) Spatial and temporal factors in weed interference with newly planted apple trees. Hort Sci 32:633–637

Mia MJ, Massetani F, Murri G, Facchi J, Monaci E, Amadio L, Neri D (2020) Integrated weed management in high density fruit orchards. Agronomy 10:1492

Miller DK, Griffin JL, Richard EP Jr (1998) Johnsongrass (*Sorghum halepense*) control and rainfastness with glyphosate and adjuvants. Weed Technol 12:617–622

Muñoz M, Torres-Pagán N, Peiró R, Guijarro R, Sánchez-Moreiras AM, Verdeguer M (2020) Phytotoxic effects of three natural compounds: pelargonic acid, carvacrol, and cinnamic aldehyde, against problematic weeds in Mediterranean crops. Agronomy 10:791

Onen H, Akdeniz M, Farooq S, Hussain M, Ozaslan C (2018) Weed flora of citrus orchards and factors affecting its distribution in western Mediterranean region of Turkey. Planta Daninha 36:018172126

Pacanoski Z, Boškov K, Mehmeti AB (2020) Replace of the EPOST glyphosate with pre herbicides and application of different LPOST glyphosate rates for weed control in established vineyard. Acta Agric Slov 116:299–310

Pittman KB, Barney JN, Flessner ML (2019) Horseweed (*Conyza canadensis*) suppression from cover crop mixtures and fall-applied residual herbicides. Weed Technol 33:303–311

Plaza G, Hoyos V, Vázquez-García, J. G., Alcántara-de la Cruz R, De Prado R (2021) First case of multiple resistance to EPSPS and PSI in *Eleusine indica* (L.) Gaertn. collected in rice and herbicide-resistant crops in Colombia. Agronomy 11:96

Radicetti E, Mancinelli R, Campiglia E (2013) Impact of managing cover crop residues on the floristic composition and species diversity of the weed community of pepper crop (*Capsicum annuum* L.). Crop Prot 44:109–119

Raimondi RT, Constantin J, Mendes RR, Oliveira RS Jr, Rios FA (2020) Glyphosate-resistant sourgrass management programs associating mowing and herbicides. Planta Daninha 38:020215928

Ribeiro VHV, Maia, LSG, Arneson NJ, Oliveira MC, Read HW, Ané JM, dos Santos JB, Werle R (2021) Influence of PRE-emergence herbicides on soybean development, root nodulation and symbiotic nitrogen fixation. Crop Prot 144:105576

Ronchi CP, Silva AA (2004) Weed control in young coffee plantations through post emergence herbicide application onto total area. Planta Daninha 22:607–615

Scarabel L, Panozzo S, Savoia W, Sattin M (2014) Target-site ACCase-resistant johnsongrass (*Sorghum halepense*) selected in summer dicot crops. Weed Technol 28:307–315

Scavo A, Mauromicale G (2020) Integrated weed management in herbaceous field crops. Agronomy 10:466

Seale JW, Bararpour T, Bond JA, Gore J, Golden BR (2020) Evaluation of preemergence and postemergence herbicide programs on weed control and weed seed suppression in Mississippi peanut (*Arachis hypogea*). Agronomy 10:1058

Tahmasebi BK, Alebrahim MT, Roldán-Gómez RA, da Silveira HM, de Carvalho LB, Alcántara-de la Cruz R, De Prado R (2018) Effectiveness of alternative herbicides on three *Conyza* species from Europe with and without glyphosate resistance. Crop Prot 112:350–355

Taskos D, Stamatiadis S, Yvin JC, Jamois F (2019) Effects of an *Ascophyllum nodosum* (L.) Le Jol. extract on grapevine yield and berry composition of a Merlot vineyard. Sci Hortic 250:27–32

Thanou ZN, Kontogiannis EG, Tsagkarakis AE (2021) Impact of weeds on *Auchenorrhyncha* incidence and species richness in citrus orchards. Phytoparasitica 49:333–347

Travlos I, Kanatas P, Tsekoura A, Gazoulis I, Papastylianou P, Kakabouki I, Antonopoulos N (2020a) Efficacy of different herbicides on *Echinochloa colona* (L.) Link control and the first case of its glyphosate resistance in Greece. Agronomy 10:1056

Travlos I, Rapti E, Gazoulis I, Kanatas P, Tataridas A, Kakabouki I, Papastylianou P (2020b) The herbicidal potential of different pelargonic acid products and essential oils against several important weed species. Agronomy 10:1687

Travlos I, Tsekoura A, Antonopoulos N, Kanatas P, Gazoulis I (2021) Novel sensor-based method (quick test) for the in-season rapid evaluation of herbicide efficacy under real field conditions in durum wheat. Weed Sci 69: 147–160

Travlos IS, Bilalis DJ, Katsenios N, De Prado R (2018) Sustainable weed control in vineyards. Pages 526–542 *in* Korres NE, Burgos NR, Duke SO, eds. Weed Control: Sustainability, Hazards, and Risks in Cropping Systems Worldwide. Boca Raton, FL: CRC Press

Travlos IS, Chachalis D (2010) Glyphosate-resistant hairy fleabane (*Conyza bonariensis*) is reported in Greece. Weed Technol 24:569–573

Travlos IS, Lysandrou M, Apostolidis V (2014) Efficacy of the herbicide GF-2581 (penoxsulam + florasulam) against broadleaf weeds in olives. Plant Soil Environ 60:574–579

Travlos IS, Montull JM, Kukorelli G, Malidza G, Dogan MN, Cheimona N, Antonopoulos N, Kanatas PJ, Zannopoulos S, Peteinatos G (2019) Key aspects on the biology, ecology and impacts of Johnsongrass [*Sorghum halepense* (L.) Pers] and the role of glyphosate and non-chemical alternative practices for the management of this weed in Europe. Agronomy 9:717

Tremblay N, Wang Z, Ma BL, Belec C, Vigneault P (2009) A comparison of crop data measured by two commercial sensors for variable-rate nitrogen application. Precis Agric 10:145–161

Tursun N, Işık D, Demir Z, Jabran K (2018) Use of living, mowed, and soil-incorporated cover crops for weed control in apricot orchards. Agronomy 8:150

Uremis I, Arslan M, Uludag A, Sangun M (2009) Allelopathic potentials of residues of 6 brassica species on johnsongrass [*Sorghum halepense* (L.) Pers.]. Afr J Biotechnol 8:3497–3501

Vazquez-Garcia JG, Palma-Bautista C, Rojano-Delgado AM, De Prado R, Menendez, J (2020) The first case of glyphosate resistance in johnsongrass (*Sorghum halepense* (L.) Pers.) in Europe. Plants 9:313

Warwick SI, Black LD (1983) The biology of Canadian weeds: 61. *Sorghum halepense* (L.) Pers. Can J Plant Sci 63:997–1014.

Wenter A, Zanotelli D, Montagnani L, Tagliavini M, Andreotti C (2018) Effect of different timings and intensities of water stress on yield and berry composition of grapevine (cv. Sauvignon blanc) in a mountain environment. Sci Hortic 236:137–145.

Wu H (2007) The biology of Australian weeds 49. *Conyza bonariensis* (L.) Cronquist. Plant Prot Q 22:122–131

Young SL (2004) Natural product herbicides for control of annual vegetation along roadsides. Weed Technol 18:580–587