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RESEARCH

Weed Control in Perennial Crops Using Hydromulch Compositions Based On the Circular Economy: Field Trial Results

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Abstract
Weed control in perennial crops is especially difficult in the first phases of crop establishment. Hydromulch is a pasty blend that hardens after application and has so far been used specifically for weed control for experimental purposes only. In this work we tested blends based on recycled paper, gypsum and lignocellulosic materials (wheat straw, rice husk and used mushroom substrate) applied in three different locations of Spain under peach, vine, almond and artichoke plantations compared with an untreated control, manual weeding and herbicide (only in artichoke). The most frequent weed species were annual and perennial forbs. Lower weed soil cover compared to the untreated control was still relevant between 333 and 456 days after mulching (DAM), depending on the trial. In the artichoke trial the weed control effect was similar to that obtained with herbicides until the end of the assessments. Annual forbs were satisfactorily controlled with hydromulches (highest for *Lamium amplexicaule* with an efficacy of 88% based on soil cover); mean efficacy of perennials such as *Cyperus rotundus* and *Convolvulus arvensis* was lower ranging between 30 and 74% efficacy depending on the trial. Multivariate analysis showed an increase in wind-dispersed species such as *Conyza* sp. and *Lactuca serriola* over time. The capacity of the mulches to reduce weed soil cover for around one year can be useful in crops where weed control is crucial during that time, such as in plant nurseries and new plantations. Future research could focus improving the durability of the mulches to extend this period.

Keywords Mulching · Biodegradable materials · Physical weed control · *Cyperus rotundus* · *Convolvulus arvensis* · *Conyza* sp.

Introduction

Weed Control in the Intra-row of Perennial Crops

Weeds can exert an important competitive pressure on young saplings of fruit, almond or olive trees and vineyards (Rupp and Anderson 1985; Gucci et al. 2012), so weed control along the row (also named as intra-row) is considered pivotal to avoid competition between the young trees and the weeds during the first years after planting (Assirelli et al. 2022) and also to avoid a delay in the onset of fruit production (Gucci et al. 2012). Additionally, uncontrolled weed growth around young trees can be a suitable place for tree-damaging rodents during the winter (Lipecki 2006).

However, weed control near the plants is not easy to perform using herbicides because of the risk of causing phytotoxicity when they reach the trunks, as green parts might absorb the herbicide (e.g. Roundup Ultimate product details, MAPA 2024; Buckelew et al. 2018). Plastic protectors around each sapling are often installed in new plantations to facilitate using these herbicides by reducing the contact risk but are not always effective enough and represent an additional cost (Liovic et al. 2013). Mechanical weed control within the row is frequent in adult vineyards

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using specific machinery but it is necessary to use it very carefully to avoid hitting the vines not only in the early development stages, being a challenging task needing a very accurate steering (Pradel et al. 2022).

Possible Alternatives

A biodegradable ground cover during the first years of tree growth limiting weed growth is attractive. The potential advantages of this technique would be avoiding soil disturbance during this period and thus allowing roots to grow also in the upper soil layer; depending on the material, soil temperature would be buffered (O'Brien et al. 2018); ideally, the biodegradable material would not need any disposal treatment and weed control would only be necessary after the material degradation. Loose organic materials such as straw, chopped bark, etc. generally require annual replacement (Hammermeister 2016); the biodegradable films used in horticulture have a too short lifespan for perennial crops (Maríet al. 2020) so that a new alternative is needed. Hydromulch consists of a pasty blend that is applied on the soil surface and usually contains paper and plant waste. Some days later, after drying out, the mixture hardens. Some commercial mixtures are sold, mainly for hydroseeding (e.g. https://www.euro-tec.es/fournitures/hydroseeding-hydromulching/) also for erosion control on construction sites or in mine restoration (Lee et al. 2018; Ricks et al. 2020). As commercial hydromulch formulations are sold for landscaping and other purposes, published work mainly refers, among other aspects, to the erosion control capacity of hydromulch and its effect on soil temperature (such as O'Brien et al. 2018), but few other publications focus on the weed control capacity of these formulations. However, potentially, hydromulch could serve as alternative to tillage or herbicide use in the first years of tree growth provided the blends are degradable and exert a sufficient weed control during a reasonable time.

The first studies on hydromulch with the specific aim of controlling weeds used cotton waste, newsprint, gypsum and a proprietary adhesive (Warnick et al. 2006). These formulations were effective for broadleaved and grass weed control but not for *Cyperus rotundus* L., which emerged successfully through the mulch layer. Shen and Zheng (2017) tested the weed control capacity of a commercial hydromulch blend based on maize, wheat, potato and soya in containers in a nursery (Advanced Micro Polymers Inc., https://www.ampolymers.com/agriculture), and found that the main drawback for weed control was the appearance of a gap between the pot wall and the dried mulch, where weeds were able to grow. However, this drawback should be less important when using hydromulch applied in larger portions on bare soil under trees or vegetable plants and not in confined conditions.

A national research project started in Spain in 2018 (RTA2015-00047-C5) with the aim of developing new hydromulch blends based on local crop residues in terms of the circular economy and to test their weed control capacity over time. Blends were applied in perennial crops in different environments and regions. Preliminary trials were conducted in growth chambers and in greenhouse conditions, studying the physical properties (Micó et al. 2019; Claramunt et al. 2020) and potential weed control capacity (Morales et al. 2019; Mas et al. 2021, 2024). Three blends with promising characteristics were chosen out of the 24 different mixtures to be tested in field conditions because they showed the highest mechanical punching resistance compared to other mixtures. The selected blends contained recycled paper slurry, gypsum and kraft fibre; the lignocellulosic components were chopped wheat straw (WS), used mushroom substrate waste (UMS) or rice husk (RH). The blends have been protected with the Spanish patent ES2817649 since 18 January 2022. Compared to WS and RH, UMS showed the lowest punching stress and needed the lowest amount of energy to be pierced (Mas et al. 2024). However, the material is available at no cost, being attractive from the economic point of view. RH showed similar stress and energy values than WS (Mas et al. 2024) but the main advantage from the practical point of view is that no milling treatment is needed to incorporate the material into the blend. Additionally, in field conditions it has been observed that hydromulch containing RH reacts differently closing initial cracks after consecutive wetting and drying processes (pers. obs.). From the punction resistance point of view WS is the most promising blend, but some drawbacks are the additional cost for milling and that cracks tend to remain once they appear. It was thus considered to test all three blends in field conditions.

In the *in vitro* trials these blends were capable of impeding seed emergence of common annual weeds (Morales et al. 2019) and also hindered rhizomes and tubers of perennial weeds from emerging by a percentage that ranged between 16 and 87% depending on the weed species (Mas et al. 2021). Moreover, all three blends were capable of reducing the number of weed shoots sprouting from the rhizomes and the emerged plants had a lower biomass than the individuals growing in non-mulched control pots (Mas et al. 2024). The solid mulches constituted a physical barrier that many rhizomes were not capable to pass through. So special care needs to be taken to maintain the mulches dry and thus hard as long as possible.

An additional general benefit of mulches in field conditions is a reduction in soil water evaporation (Kader et al. 2019), e.g. with straw mulch (Arora et al. 2011); rice straw used as mulch was capable of reducing the soil evaporation by up to 35–40 mm in irrigated wheat (Balwinder-Singh et al. 2011). For hydromulches this effect has also been found, as escarole plants had a superior growth, due to improved plant water relations and photosynthetic function, in comparison with non-mulched plants in drought stress conditions (Romero-Muñoz et al. 2022a).

Due to the stepwise degradation of the mulches, these materials could also serve mid-term as a source of nutrients (Iqbal et al. 2020). In the case of using hydromulch based on UMS, growth of escarole was increased due to a more efficient use of nitrogen and phosphorous (Romero-Muñoz et al. 2022b). Organic mulch decays over time and adds nutrients to the soil as it breaks down (Ning and Hu 1990); it increases long-term nutrient availability in the soil (Larentzaki et al. 2008) and works as fertilizer. Mulches may increase soil nutrients for crop growth and development after decomposition under appropriate water and temperature conditions thanks to the soil microbial populations (Chalker-Scott 2007; Wang et al. 2018).

The aims of this work were a) to describe the weed control capacity of three previously selected hydromulch types in different locations subjected to diverse weed populations over several months, b) to obtain data on the weed control duration of the mulches, and c) to identify the possible drawbacks of using the hydromulches in real field conditions.

Materials and Methods

Experimental Design and Trial Installation

We conducted a joint field trial series in three different locations on four crops: a peach orchard and a vineyard in Montañana (Zaragoza), an almond orchard in Ciudad Real and an artichoke plantation in Murcia (Table 1; Fig. 1). The ages of the plantations varied between 0 and 6 years (Table 1).

All trials included 1) untreated control plots, 2) manually weeded control plots (in Murcia replaced by herbicide use), 3) WS mulch, 4) UMS mulch, and 5) RH mulch. Additionally, WS, UMS and RH with half of the gypsum content were tested in the peach trial; RH with linseed oil applied on the surface (RH oil) was also tested in the vineyard and the almond orchards with the aim of reducing the wetting of the mulches in the event of rainfall. The application rate of the oil was 100 ml m^{-2} applied with a manual sprayer (Matabi trademark) using a Teejet 110-03 blue ceramic nozzle (VK) on 16 July 2019 and repeated on 27 September 2019 in the vineyard (due to the abundant rainfall recorded in July and August) and on 28 May 2019 in the almond trial.

The mulches were applied from winter 2018 to spring 2019. Except for the gypsum, the rest of the ingredients were shared and thus identical in all field trials. Blends were mixed *in situ* with a stirrer and mulch applied manually immediately afterwards. Components were 16.71 m^{-2} recycled paper slurry produced in the Saica paper factory (El Burgo de Ebro, Zaragoza) containing 5% solid matter, 1002 g m^{-2} fast-solidifying gypsum, 209.25 g m^{-2} kraft fibre (Capellades Paper Mill Museum, Capellades, Spain); the three types contained either (1) 833 g m^{-2} WS (internal production by CITA), (2) 3100 g m^{-2} UMS generated by the mushroom (*Agaricus bisporus*) production industry (provided by Sustratos de la Rioja SL, La Rioja, Spain) or (3) 1250 m^{-2} g RH provided by the company Arrocera del Pirineo (Alcolea de Cinca, Huesca, Spain). Recycled paper slurry was used for its fibrous structure forming the matrix of the blend and kraft fiber was added because of its hardening effect, as its fibers are longer than the ones of the recycled paper. Gypsum was added for its solidifying properties. The lignocellulosic components (WS, RH and UMS) were added to extent the duration of the blend, as observed in preliminary trials (Baquero 2018). Testing half of gypsum dose was considered in two trials to potentially reduce the blend cost and gypsum input into the soil.

To stop the gypsum hardening too soon, portions for one elementary plot were prepared individually and placed manually on the soil as fast as possible. The elementary plots were continuous in all trials except in the peach orchard due to the large distance between trees; there, five individual portions measuring 1 m^2 were applied separately, each one under one tree (Table 1). Wooden or metal frames were used to confine the hydromulch to the desired areas.

Periodically, it was decided to mow the weed rests growing in the untreated plots and in the mulches after reaching maturity due to their considerable height and biomass to allow the measurement of the cracks in the mulches (results not shown in this paper) and to follow up the degradation of the hydromulches. In the trials conditions there are two

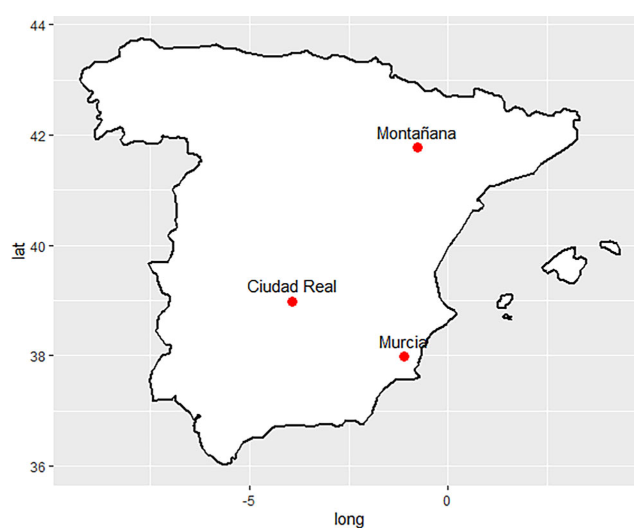


Fig. 1 Map of Spain showing the locations where the field trials were conducted

Table 1 Location of the fields, plantation age at mulching, soil type, mulching date and mowing time of emerging weeds at the different locations. In parentheses, days after mulching

Location (crop)/age of plantation	Latitude/longitude	Soil type	Mulch installation date	Mulch size per elementary plot	Mowing of emerged weeds in the mulch plots	Mechanical weeding in the hand weeding treatment***	Distance between crop plants × between lines (m)
Montañana (peach)/ 10 months	41°43′45.49″N 0°48′28.54″W	Loam	03/12/2018	5 times 1 m^2	12/04/19 (130) 15/09/19 (285) 29/10/19 (200)	21/05/19 (39) 22/07/19 (73) 04/10/19 (175) 28/02/20 (322)	4×6
Montañana (vine)/ 1 month	41°43′48.04″N 0°48′24.87″W	Loam	14/03/2019	5 m × 1 m in a strip	11/07/19 (112) 23/04/20 (407)	21/05/19 (68) 22/07/19 (123) 27/09/19 (190)	1×3.5
Ciudad Real (almond)/ 6 years	39°0′N 3°56′W	Sandy loam	06/05/2019	6 m × 1 m in a strip	22/07/2019 (78) 11/10/2019 (159) 03/04/2020 (334) 16/06/2020 (408) 25/09/2020 (509)	22/07/2019 (78) 11/10/2019 (159) 03/04/2020 (334) 16/06/2020 (408) 25/09/2020 (509)	1.2×3.5
Murcia (artichoke)/ planted 2 days before	37°45′N; 0°59′W	Clay loam	08/08/2018	10 m × 0.8 m in a strip	14/08/18 (6) 21/08/18 (13) 28/08/18 (20) 04/09/18 (27) 04/10/18 (57) 08/11/18 (92) 19/12/18 (133) 16/01/19 (161) 19/02/19 (195)***	11/09/18 (34)* 19/10/18 (103)** 21/12/18 (135)*	1×2

*Herbicide was applied instead of hand weeding: diquat 20% (Reglone©), 3 l ha^{-1}

** Piridate 45% (Lentagram©), 1 kg ha^{-1}

***In Murcia, emerged weeds were cut in all plots after each sampling date

marked seasons for weed emergence, one in autumn-winter and a second one in spring-summer. Mowing the weeds after noting down the weed soil cover in maturity of the weeds allowed to start again a new season and to assess the effect of the mulches on new weed emergences after removing the plant rests.

In the peach trial the starting density of *Cyperus rotundus* L. was very high and the mulches controlled emergence only partially; moreover, the leaves lifted the mulches, damaging them. Thus, in this trial the weeds needed to be cut three times during the year 2019 in all plots. Unfortunately, mobility restrictions during the COVID-19 pandemic impeded mowing in spring and summer 2020 in the peach orchard and degradation of the mulches was probably accelerated in that period.

In the vineyard, the summer weeds with highest cover were *Polygonum aviculare* L. and *Convolvulus arvensis* L., so mowing was done in spring/summer in both 2019 and 2020; in the almond trials especially the summer weeds *Conyza* sp., *C. arvensis* and *Salsola kali* L. made it necessary to cut the plants in the summers of 2019 and 2020; the species *Stellaria media* (L.) Vill. led to mowing in the autumns of 2019 and 2020.

Hoeing in the manually weeded treatment was done when considered necessary to keep the plots reasonably weed-free (Table 1); herbicide was used in the artichoke three times during the experimental period when weeds were sufficiently developed.

Drip irrigation was used in all trials, the pipes and emitters being buried in the soil at a depth of 5–10 cm to avoid the repeated wetting and weakening of the mulches. In the almond orchard, the high stoniness hindered the burial, so part of the hydromulches was wet for several days after each irrigation. Therefore, two different areas were considered for data collection in each plot: a) the part that was always dry and b) the part that was intermittently wet.

In Murcia data collection was conducted from August 2018 until the end of the harvest in February 2019. It was planned to continue sampling after August 2019 but a storm occurring on 12 September 2019 flooded the trial, which had to be abandoned. Considering that artichoke is a horticultural crop, weed samplings were carried out at higher frequency than in the other trials in orchards, but for a shorter period of time.

Data Collection

Total and specific weed soil cover of each weed species was assessed visually in each plot by at least two trained people

Table 2 Weed data collection in dates and days after mulching (DAM)

Location (crop)	Weed assessment date and DAM
Montañana (peach)	20/01/19 (47), 13/02/19 (71), 22/03/19 (108), 02/05/19 (149), 31/05/19 (178), 15/07/19 (223), 02/09/19 (272), 28/10/19 (328), 12/12/19 (373), 11/02/20 (435)
Montañana (vine)	06/05/19 (54), 07/06/19 (86), 08/07/19 (117), 02/09/19 (173), 30/09/19 (201), 12/12/19 (274), 20/02/20 (344), 23/04/20 (407), 11/06/20 (456)
Ciudad Real (almond)	27/6/2019 (53), 15/7/2019 (71), 3/9/2019 (121), 1/10/2019 (149), 19/11/2019 (198), 15/1/2020 (255), 3/4/2020 (334), 16/6/2020 (408), 25/9/2020 (509)
Murcia (artichoke)	14/08/18 (6), 21/08/18 (13), 28/08/18 (20), 04/09/18 (27), 04/10/18 (57), 08/11/18 (92), 19/12/18 (133), 16/01/19 (161), 19/02/19 (195)

periodically (Table 2). In Murcia data was recorded for each 0.8 m^2 plot and in the rest of trials for each individual 1 m^2.

Data Analysis

Weed frequency and richness were calculated for all plots and species and mean values estimated. Total mean weed soil cover data was computed for each assessment date and treatment; for the most frequent species in each trial the mean soil cover was also estimated across all the assessment dates. Data was analysed for normality and homoscedasticity and, when necessary, transformed using asin$(\sqrt{x}/100)$. When the criteria were fulfilled, ANOVAs and Tukey mean separation tests were conducted for mean weed soil cover using R version 2.15.0 (R Core Development Team 2019).

Soil cover of each weed species was used for canonical correspondence analysis (CCA) where the three variables location, treatment and day after mulching (DAM) were introduced according to the forward selection procedure using CANOCO version 5 (Smilauer and Leps 2014). Due to the mowing after each data collection, data from Murcia was not included in the multivariate analysis.

Climatic Data

Maximum, minimum and mean temperatures as well as monthly rainfall were retrieved from the nearest meteorological stations (Table 3). In Zaragoza and Ciudad Real heavy rainfall occurred five months after application, but in Murcia as early as one month after installation (Table 3).

Results

Predominant Weed Species

The most frequent weed species in the untreated control plots were different in each location; however, two annual forbs and one perennial weed species were among the most frequent species in the peach, vine and almond trials (Table 4). In the artichoke, three annual forbs were the most frequent species. Grasses was the least frequent group: no single species is included in the list of the three most frequent species in any of the experimental locations (Table 4).

Water availability had an influence on the most frequent species in the almond orchard: the perennial creeping *C. arvensis* was 50% more frequent in the moist than in the dry mulch parts; the third most frequent species were two annual forbs, *Diplotaxis virgata* (Cav.) DC in the dry part and the creeping *S. media* in the moist part.

Species richness was highest in the vine and peach trials in Montañana, followed by the moist part of the almond trial in Ciudad Real, and was lowest in Murcia (Table 4).

Weed Soil Cover

Weed abundance in terms of weed soil cover was much higher in the peach orchard and in the vineyard than in the rest of the trials and was also much higher in the moist part of the almond plots than in the dry ones (Figs. 2, 3, 4, 5, 6 and 7).

Weed soil cover was generally the highest in the untreated plots in all trials. The weed control effect of the various mulches was still appreciable in terms of a reduced weed soil cover showing significant differences in the ANOVAs until 435, 456, 333 and 333 DAM in the peach, vine, and dry and moist part of the almond trials, respectively. The suppressing effect of the mulches was less persistent for the moist part of the almond trial, significantly lower for the mulches compared to the untreaded plots until 333 DAM and continued the tendency onwards (Fig. 2).

Overall, WS was the mulch most capable of reducing weed soil cover, RH was intermediate and USM had generally the worst weed control efficacy in terms of weed soil cover.

In the peach trial, using a larger amount of gypsum did not lead to significantly higher weed control in any of the three mulches; from the weed control point of view using less gypsum was sufficient. Likewise, spraying linseed oil on the RH mulch did not have a significant effect on the weed soil cover in either of the two trials in which it was tested.

In the artichoke trial, the weed control in the mulched treatments was statistically similar to the herbicide effect obtained at 29 DAM onwards (Fig. 2).

Table 3 Monthly air temperature (maximum: Tmax; minimum: Tmin; mean: Tmean) and rainfall during the trial periods in the three locations. Climatic data from meteorological stations provided by the Oficina del Regante (Gobierno de Aragón) for Zaragoza, by the Spanish Ministry of Agriculture, Fishery and Food (MAPA) for Ciudad Real, and by the SIAM (Sistema de Información Agraria de Murcia) for Murcia

Year	Month	Montañana (Zaragoza)				Ciudad Real				Murcia			
		Tmax (°C)	Tmin (°C)	Tmean (°C)	Rainfall (mm)	Tmax (°C)	Tmin (°C)	Tmean (°C)	Rainfall (mm)	Tmax (°C)	Tmin (°C)	Tmean (°C)	Rainfall (mm)
2018	Aug	–	–	–	–	–	–	–	–	31.0	25.6	27.2	0.1
	Sept	–	–	–	–	–	–	–	–	26.8	21.1	24.7	65.3
	Oct	–	–	–	–	–	–	–	–	22.1	12.6	19.1	61.0
	Nov	–	–	–	–	–	–	–	–	18.0	11.0	14.5	75.1
	Dec	12.8	2.8	7.8	12.9	–	–	–	–	14.5	9.2	12.3	14.8
2019	Jan	11.3	1.9	6.2	17.2	–	–	–	–	22.8	–0.7	10.9	2.0
	Feb	16.8	0.5	8.6	5.4	–	–	–	–	25.9	0.5	11.8	0.1
	Mar	19.1	2.6	10.8	5.4	–	–	–	–	28.9	2.7	13.5	20.4
	Apr	19.3	6.5	12.9	40.4	–	–	–	–	27.8	6.2	15.6	116.4
	May	23.8	9.0	16.4	41.2	26.0	8.2	17.6	2.0	–	–	–	–
	Jun	30.8	13.2	22.0	3.2	31.0	11.3	22.1	2.6	–	–	–	–
	Jul	33.4	17.3	25.3	28.5	35.0	16.3	26.2	3.2	–	–	–	–
	Aug	32.8	16.9	24.8	39.6	34.0	15.1	25.1	0.0	–	–	–	–
	Sept	28.0	13.3	20.7	6.0	28.0	12.6	20.1	57.7	–	–	–	–
	Oct	23.2	10.5	16.8	30.9	23.4	7.7	15.3	24.9	–	–	–	–
	Nov	15.3	4.8	10.0	43.4	13.3	4.6	9.0	76.8	–	–	–	–
	Dec	12.9	3.5	8.2	42.6	11.9	3.0	7.0	69.9	–	–	–	–
2020	Jan	10.1	1.0	5.5	60.6	10.3	–0.7	4.2	17.8	–	–	–	–
	Feb	17.5	2.6	10.1	3.2	15.1	0.2	6.9	3.4	–	–	–	–
	Mar	16.7	4.7	10.7	67.7	16.2	3.3	9.6	60.3	–	–	–	–
	Apr	20.7	8.8	14.7	49.9	18.6	6.8	12.5	29.9	–	–	–	–
	May	26.7	11.7	19.2	86.0	26.9	9.3	18.2	25.9	–	–	–	–
	Jun	28.2	13.8	21.0	53.9	30.2	12.0	22.0	1.1	–	–	–	–
	Jul	–	–	–	–	37.4	17.5	28.0	1.9	–	–	–	–
	Aug	–	–	–	–	34.5	15.4	25.3	14.9	–	–	–	–
	Sept	–	–	–	–	28.4	12.0	20.3	8.2	–	–	–	–

Table 4 The three most frequent species in the untreated control plots at all sampling dates (% of occurrence in the sampled plots) and species richness in the different locations

	Montañana peach	Montañana vine	Ciudad Real almond (dry)	Ciudad Real almond (moist)	Murcia artichoke
Most frequent species	*Cyperus rotundus* (90)	*Sonchus oleraceus* (66)	*Conyza* sp. (79)	*Convolvulus arvensis* (82)	*Amaranthus* sp. (59)
Second most frequent species	*Lamium amplexicaule* (80)	*Polygonum aviculare* (65)	*Convolvulus arvensis* (34)	*Conyza* sp. (81)	*Urtica urens* (58)
Third most frequent species	*Sisymbrium irio* (67)	*Convolvulus arvensis* (61)	*Diplotaxis virgata* (27)	*Stellaria media* (51)	*Portulaca oleracea* (45)
Total species richness	41	49	19	24	13

Heavy rainfall recorded in Ciudad Real around 240 DAM and in Zaragoza around 120 and 150 DAM provoked an increase of weed cover in all treatments, especially in the control plots (Fig. 2). The same was observed after the unusual rainfall occurring in January and March to June 2020 in Zaragoza (this is around 400 DAM), in this case conducing to the finalization of the trials.

Soil Cover of the Most Frequent Weeds in the Peach Trial

Mean soil cover of the perennial species *C. rotundus* was only significantly reduced by the RH hydromulch treatment compared to the untreated plots, although the rest of the mulches also tended to decrease nutsedge soil cover, especially WS with high gypsum dose (Fig. 3). However, mowing was necessary several times in all the plots to keep the mulches intact as long as possible because the plants not only pierced but also lifted the mulches prior to unfolding the leaves.

The annual winter germinating species *Lamium amplexicaule* L. was in general effectively controlled with all the tested mulches achieving a mean efficacy of 88%; *Sisymbrium irio* L. soil cover reduction was generally poorer, probably due to the greater size of this species causing a higher plant soil cover, but control was best with the two WS mulches (89%). No significant differences in weed control of the main species were observed when using gyp-

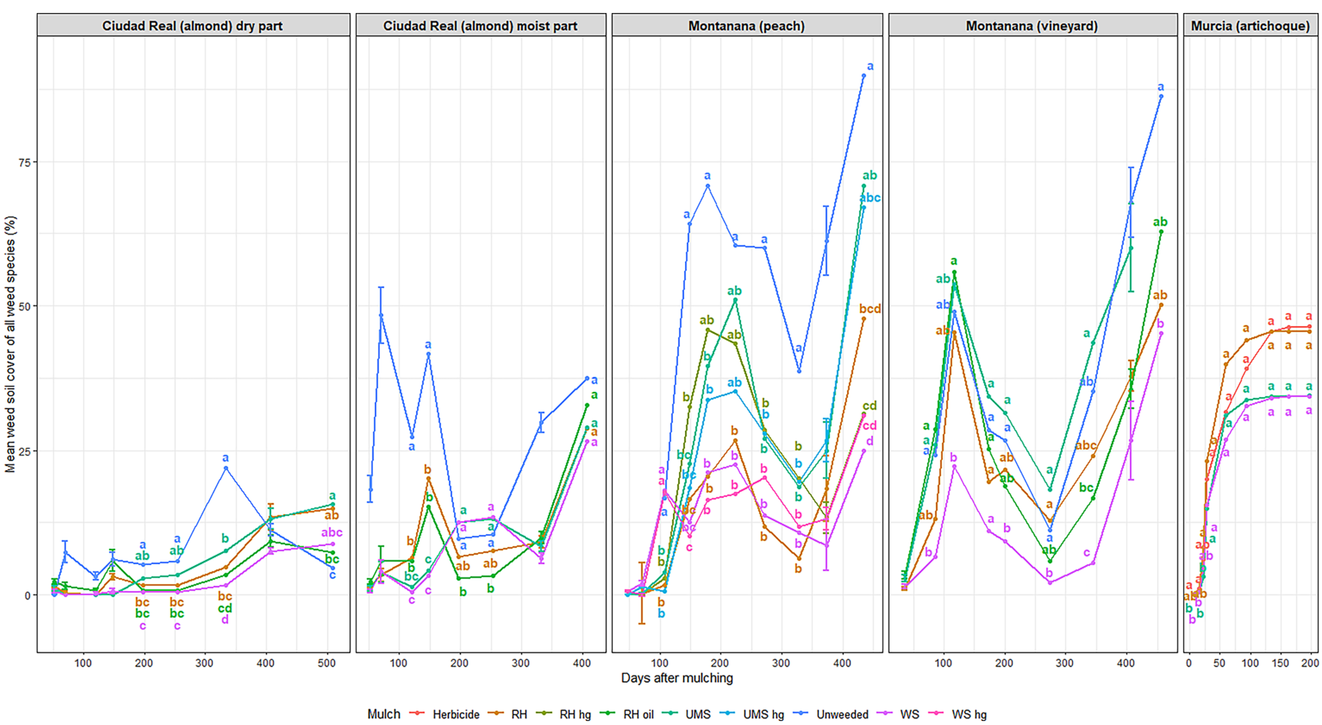
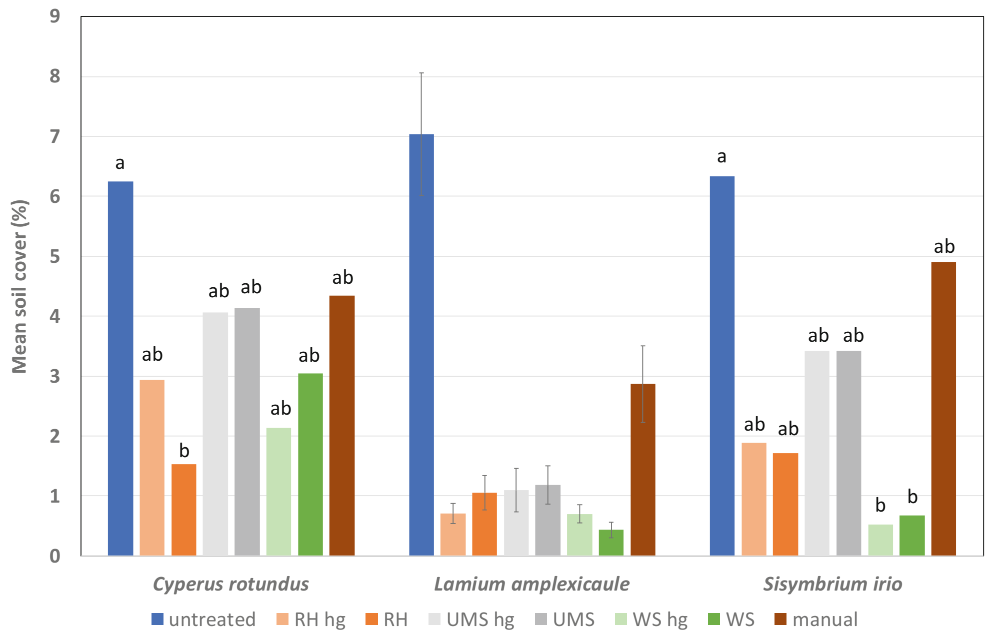


Fig. 2 Mean weed soil cover of all weed species (%) in the untreated control plots and in the hydromulch treatments. *DAM* days after mulch installation. Mulches based on *WS* wheat straw, *RH* rice husk, *UMS* used mushroom substrate, *hg* half gypsum dose, *oil* surface application of linseed oil. Different letters in each column for each trial represent significant differences using Tukey mean separation tests with $P < 0.005$. *Data back-transformed from asin($\sqrt{x}$/100). In Murcia: additive values from the previous assessment dates because weeds were mown after each assessment

Fig. 3 Mean weed soil cover in all the treatments at all the assessment dates of the three most frequent species ± standard error in the untreated control plots in the peach trial. Hg: half gypsum dose. Significant differences are indicated with different letters within one species. Data back-transformed from asin $(\sqrt{x}/100)$



sum at different dosages for any of the three different base ingredients.

Soil Cover of the Most Frequent Weeds in the Vine Trial

The perennial summer species *C. arvensis* was only partially controlled with the RH mulch (69% efficacy) but reached high mean soil cover in all the other treatments, including the manual weeding. WS was the hydromulch treatment that controlled the other two forb species best (82% and 53% for *P. aviculare* and *S. oleraceus*, respectively), similarly to the manual weeding treatment (Fig. 4). Weed control was similar with RH and RH oil, except for *C. arvensis*, which curiously covered the soil much more in RH sprayed with oil than in the simple RH treatment.

Soil Cover of the Most Frequent Weeds in the Almond Trial

As expected, weed soil cover was much higher in the moist than in the dry part of the almond trial, both for the species *C. arvensis* and for *Conyza* sp.; however, the mulches were capable of reducing *C. arvensis* soil cover, especially UMS and WS in both situations (Figs. 5 and 6), unlike the poor control observed in the vineyard (Fig. 4). Efficacy in the dry part was 31, 76 and 90% for RH, WS and UMS, respectively and in the moist part 58, 78 and 87% for the same treatments. Similarly to what was observed in the vineyard, also in the almond trial the weed *C. arvensis* had a higher soil cover in the RH oil treatments than in the RH; however, RH oil was capable of reducing the mean weed soil cover of *Conyza* sp. compared to RH in the dry part (Fig. 5).

Concerning the annual forbs, *Diplotaxis virgata* (Cav.) DC (dry part) was best controlled with WS, RH oil and RH (97, 97 and 95% efficacy, respectively), and *S. media* (moist part) with RH oil and RH (89 and 69% efficacy, respectively). Cover reduction of *Conyza* sp. was around 50% in both parts, significantly lower soil cover being achieved with RH oil and WS in the dry part and with all the mulches in the moist part (Figs. 5 and 6).

Soil Cover of the Most Frequent Weeds in the Artichoke Trial

In Murcia, WS and RH achieved a lower mean soil cover for *Amaranthus* sp. than the herbicide and manual control. UMS had an intermediate efficacy (78, 68 and 27% efficacy for WS, RH and UMS, respectively) (Fig. 7), while all the mulches achieved a similar soil cover of *P. oleracea* to the herbicide and manual weeding treatments. All the mulches showed a lower soil cover of *Urtica* sp. than the herbicide and the manual weeding.

Weed Species Composition Depending On the Different Treatments

An overall CCA with all the species' soil cover data collected in the four trials and at all the sampling moments explained only 9.1% of the total variation and revealed that the most important factor explaining species composition was the site, followed by the DAM and, finally, the treatments (data not shown). Thus, it was decided to analyse the different locations separately to be able to appreciate the effect of the treatments on weed composition in more detail. In all four CCAs per site, DAM was the factor explaining most of the variation, although the treatments always had a significant contribution, too. Due to the emergence of *Echinochloa* spp. in the RH in Ciudad Real, the CCAs

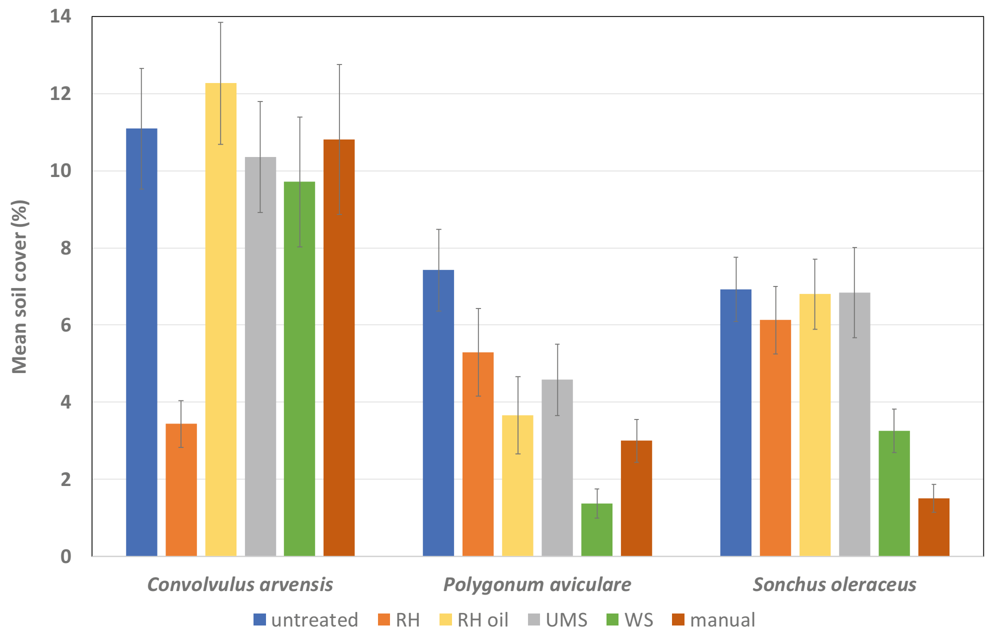


Fig. 4 Mean weed soil cover in all the treatments at all the assessment dates ± standard error of the three most frequent species in the untreated control plots in the vine trial. *RH oil* rice husk with linseed oil application on the surface

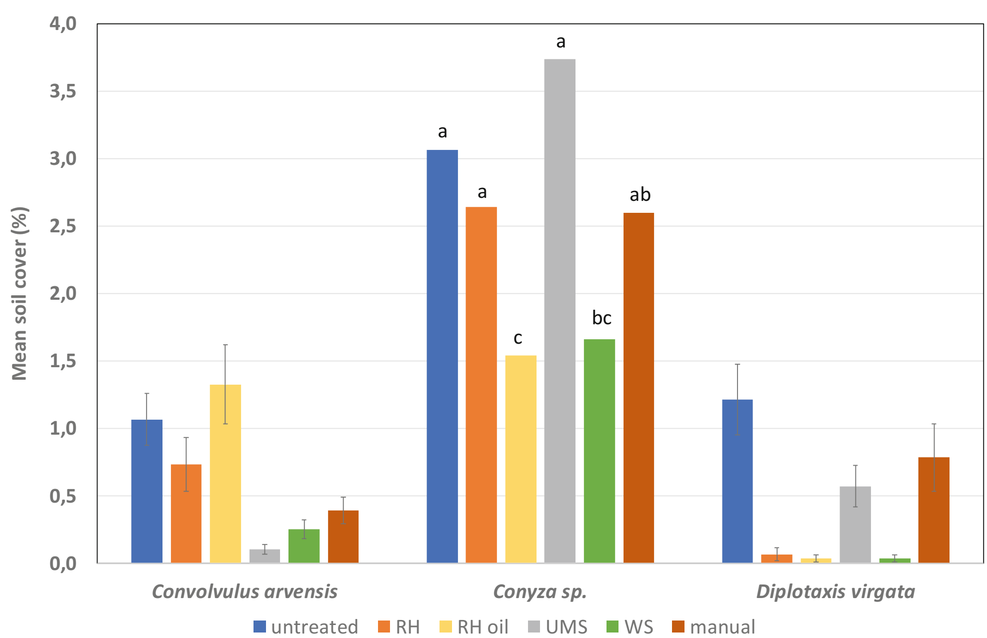


Fig. 5 Mean weed soil cover in all the treatments at all the assessment dates ± standard error of the three most frequent species in the untreated control plots in the dry part of the almond trial. *RH oil* rice husk with linseed oil application on the surface. Significant differences are indicated with different letters within one species. Data back-transformed from asin $(\sqrt{x}/100)$

of the almond trials were very biased, so it was decided to remove this species from the analysis. In Zaragoza, the RH was subjected to 60 °C for seven days, which devitalized the *Echinochloa* seeds, preventing their germination in the trials in that location.

The explained variation was higher in the CCAs analysing data of the locations separately than all of them together (Table 5), justifying the individual analysis. In most of the trials groups of annual species were related to certain sampling moments; spring and summer germinating species were associated with sampling moments 2–5 in the vine, 4–6 in the peach, and 2–4 in the moist part of the almond trial. In contrast, autumn and winter emerging weeds were related to sampling moments 6–8 in the vine, and 5–6 in the moist part of the almond trial (Figs. 8, 9, 10 and 11). Wind-dispersed species such as *Conyza* sp., *L. serriola, S. oleraceus, P. laciniatum*, and *P. echioides* were related to the latest sampling moments (8 and 9 in vine and peach, sampling moment 5 onwards in the dry part of the almond trial and 7 and 8 in the moist part). This means that their importance (abundancy and frequency) increased in time. Likewise, perennial species such as *Foeniculum vulgare* Mill. and *M. sylvestris*, biennials such as *Onopordum acanthium* L. and creeping species such as *Tribulus terrestris* L. were located nearer to the later sampling moments.

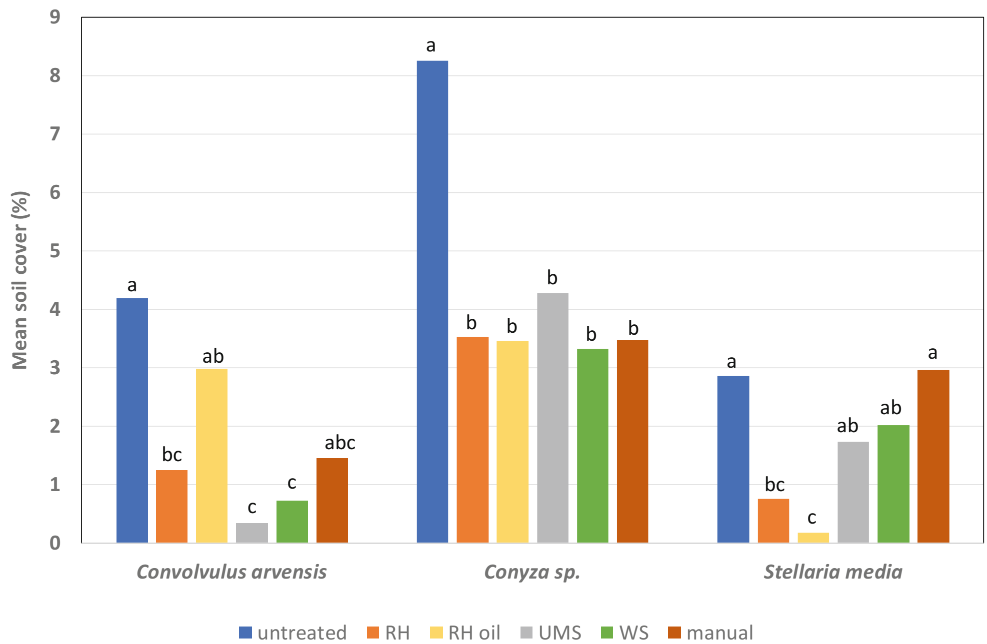


Fig. 6 Mean weed soil cover in all the treatments at all the assessment dates of the three most frequent species in the untreated control plots in the moist part of the almond trial. *RH oil* rice husk with linseed oil application on the surface. Data back-transformed from asin $(\sqrt{x}/100)$

In contrast, some species were quite centred in the graphs in several of the trials, demonstrating a higher independence on both the sampling moment and the treatment: *S. oleraceus* in the vineyard, and *C. arvensis* in all four trials, showing it is a species that is difficult to control, present in many sampling sites, at different moments and in all kinds of treatments.

Concerning the treatments, the untreated and manually weeded treatments were grouped separately from the hydromulches in all four trials, showing that the mulches were somehow associated with a different weed composition. Within the mulches, UMS was closest to the manual treatment (vine and dry part of the almond trial); WS and RH were quite close to each other in all four trials except for the peach trial, where WS was the most efficient in reducing weed soil cover (Figs. 2 and 3).

Discussion

Predominant Weed Species

Vegetables had been grown in the peach plot for many years before planting, justifying the high *C. rotundus* den-

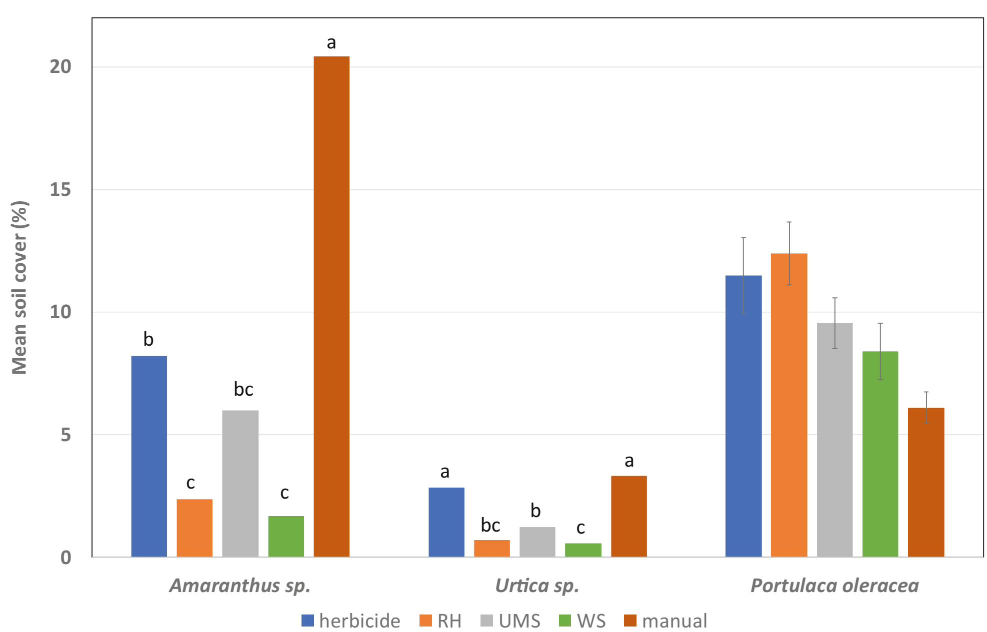


Fig. 7 Mean weed soil cover in all the treatments at all the assessment dates ± standard error of the three most frequent species in the untreated control plots in the artichoke trial in Murcia. Due to the periodic mowing, mean values of the accumulated sum are shown. Data back-transformed from asin $(\sqrt{x}/100)$

Table 5 Results of the CCA analysis

	Total variation (%)	Explained variation (%)	Explained fitted variation Axis 1 (%)	Explained fitted variation Axis 2 (%)
Vine (ZZA)	9.3	11.6	30.9	49.0
Peach (ZZA)	9.9	16.7	35.1	56.4
Almond dry (CR)	9.1	19.5	34.9	58.6
Almond moist (CR)	7.8	21.1	34.6	59.8

sity, common in vegetables but less problematic in orchards because this species is susceptible to competition (Morales-Payan et al. 2003). Thus, in the untreated control plots abundance of this species is expected to diminish due to the competition of the other weed species, as has been observed in other trials (Maríet al. 2020).

In the vineyard, annual forage crops had been grown for many years before the grapevines were planted; *C. arvensis* is not a typical species in annual forage crops, so its abundance is probably an adaptation to the lack of tillage in the new plantations. Indeed, Hettinger et al. (2023) found that *C. arvensis* density remained low in intensively tilled fallow treatments or in perennial alfalfa treatments but was more variable in treatments with minimal to moderate tillage.

In Ciudad Real the almond orchard was planted six years earlier, so the detected weed species were already adapted to orchards. In Murcia, a lettuce crop had been grown in the experimental field for the three previous years and the annual tillage of the plots all these years probably prevented the predominance of perennial species. On the other hand,

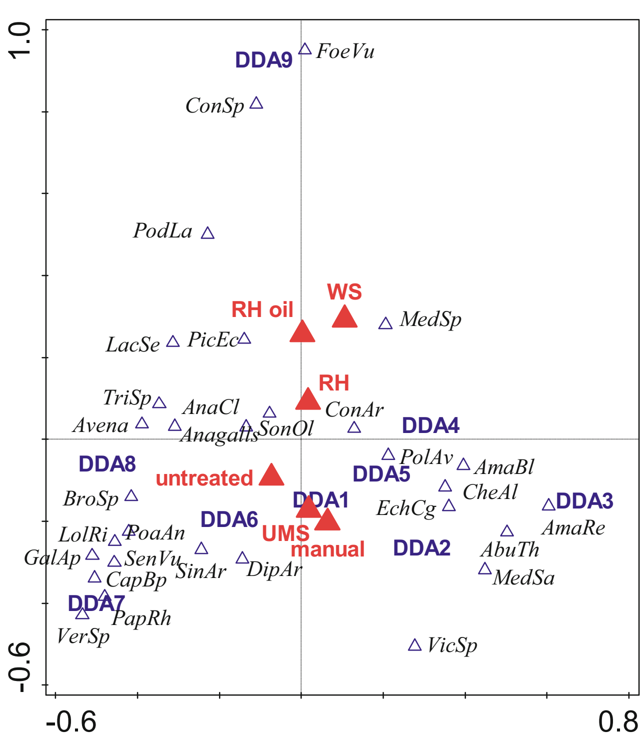


Fig. 8 CCA analysis for the vine trial. Plants are named with the first three letters of the genus and first two of the species

as expected in horticultural land, all three dominant species in this location were typically nitrophilous. Several annual forbs were frequent in Montañana and Ciudad Real, the wind-dispersed species *Sonchus oleraceus* L. and *Conyza* sp. being the most representative group. Probably due to its dispersion mechanism based on wind (Bastida et al. 2021), *Conyza* sp. had a similar frequency in the moist and the dry part of the mulches.

Weed Soil Cover in the Different Treatments and Locations

Annual species were generally well controlled by the hydromulches in all trials; only species with high biomass production such as *S. irio* and *S. oleraceus* showed moderate soil cover values compared to the untreated control plots. The same hydromulch formulations as tested in the artichoke plantation had been found to effectively control the emergence of annual weed species in pots (Morales et al. 2019). When considering the three most frequent species, highest efficacy was more often for WS (10 times), followed by RH (3 times) and by UMS (2 times). This result is probably related to the physical structure of the blends. The wheat straw of the WS was integer while the straw of the UMS had been previously used for mushrooms cultivation and was thus weaker and probably easier to pierce by weeds. On the other hand, RH particle size was bigger than the milled straw used in WS offering thus weeds more space to grow through.

C. rotundus pierces polyethylene or biodegradable mulch films but has been found to be effectively controlled with paper sheets provided the paper remains dry (Cirujeda et al. 2012; Maríet al. 2020). Hydromulches thus seem to offer an intermediate resistance to this species compared to these two groups of mulches, which seems logical, as the paper consists in a homogeneous hard barrier, the hydromulch being mixed with other components. Indeed, greenhouse experiments showed that the capacity of the three tested hydromulches to reduce rhizome sprouting stood at around only 16% for *C. rotundus* tuber emergence (Mas et al. 2021), but higher control was achieved concerning emerged shoots (best with RH, with 77% efficacy) and biomass reduction (72% with RH) (Mas et al. 2024). In the field trial shown here, RH also achieved the highest control concerning soil cover values (Fig. 3). In the greenhouse trials most of the emergences occurred soon after the mulches were installed and before they had hardened; however, in the field trial the mulches remained moist several times after rainfall periods and emergences thus occurred over longer periods. Despite these differences, weed control values based on soil cover were similar to those observed in the pot trials (Fig. 3).

Concerning the other perennial species, *C. arvensis*, results were irregular between the two locations (vine and almond). This species reproduces mainly vegetatively, thus appearing in patches that have been found to be relatively stable (Jurado-Expósito et al. 2004), so a patchy distribution in the vineyard plot, where this species was probably only starting to grow (it is not a typical species in the previous forage crops), might have been a factor explaining this result. The unexpected differences found in the efficacy of RH and RH oil with this species are probably explained by an irregular distribution of these weeds.

Regarding the difficulty in controlling *Conyza* sp. in the almond orchard, part of the infestation of this species can be due to wind-dispersed seeds arriving from nearby plantations and germinating on the mulches. Indeed, next to the experimental field, weeds of other plantations are managed with glyphosate and dominated by *Conyza* plants that probably exhibit herbicide resistance. Moreover, a *Conyza* seeds have been found to be unable to germinate from depth; maximum emergence rates are found when they are located on the soil surface and less than 10% emergence occurs at 1 cm depth in soil (Vidal et al. 2007) suggesting that the origin is probably not the seedbank of the experimental plantation but the nearby orchards.

Thus, most of the plants found had either regrown from older plants or germinated from the surface of the hydromulches. Following the results, in the moist part, all three hydromulches served *Conyza* similarly as a substrate for germinating; opposite, in the dry part of the mulches, RH treated with oil as well as WS showed a lower *Conyza* emergence, probably because their physical properties were less appropriate for the plants to grow on them (Figs. 5 and 6). Unlike polyethylene film mulches, most of the tested hydromulches offer the seeds a substrate that is very probably suitable for them to germinate when they are located on the top of the hydromulch layer, especially after rainfall, which may be a drawback of these kinds of mulches.

Generally, more perennial weeds are expected in older plantations rather than in newly-planted ones; in those cases, hydromulch will probably be less effective. Punching resistance in the mulches containing a higher gypsum dosage has been found to be higher (data not shown), so it is supposed that these mulches offer a higher resistance to weeds that clearly pierce the soil surface when germinating. However, not only punction resistance but also other factors probably play a role in the capacity of resisting weed emergence, because RH with higher gypsum content tended to reduce *C. rotundus* emergence, while in UMS no differences in the emergence of this species between both gypsum content values were found at all and in WS, the mulch with higher gypsum content tended to show even a higher *C. rotundus* soil cover than the one with lower content (Fig. 3). Concerning the control of annual weed species (Fig. 3) no tendencies at all were found when using higher or lower gypsum content for none of the three crop residues. These results are in accordance with those of Morales et al. (2019) describing a similar weed emergence of both grasses and broadleaved species when using half gypsum dosage compared to the full dosage. Thus, no clear recommendation for using lower or higher gypsum rate in the mulches can be made from the weed control point of view.

Concerning the application of oil on RH, heavy rainfall washed the oil away in the vineyard; the only significant effect was observed for *Conyza* sp. control in the dry part of the almond trial. This aspect probably requires further investigations.

Multivariate Analysis

The result of wind-dispersed species being more related to later assessment dates is coherent with the observations of other researchers associating *Conyza bonariensis* (L.) Cronquist (Zambrano-Navea et al. 2016; Zaplata et al. 2011), *S. oleraceus* (Widderick et al. 2002) *L. serriola* (Ruisi et al. 2015) and *P. echioides* (Pardo et al. 2019) with non-tillage in Mediterranean areas in several crops such as citrus and olive orchards. The relative distance from the hydromulches WS and RH to the untreated control on one hand confirms the results found with the mean weed soil cover, and on the other hand stresses the increase in wind-dispersed weed species over time. These results indicate that probably most of the seeds of these species have germinated on the top of the mulches after wind-dispersal and did not germinate from the seed bank piercing the mulches.

The results of the multivariate analysis also confirm the findings of the weed soil cover analysis (Fig. 2): WS and RH were generally more different from the untreated control, while UMS did not achieve such a different weed composition from the untreated control. Thus, both data analyses led to similar conclusions.

Overall Weed Control in the Trials

The mulches made with RH and WS were capable of reducing the mean soil cover of annual and perennial weeds in several field trials. UMS showed the lowest weed control capacity, probably due to its faster weakening of the punching resistance over time compared to RH and WS

(Mas et al. 2024). The soil cover reduction of perennial species was more irregular than for annual species, probably depending on other factors such as initial density in the fields and the duration of the periods in which the mulches were soft due to moisture. The visual observations suggest that weeds emerge easier after rain events, especially if the mulches remain wet during a long period. Ideally, the hydromulches should allow rainfall reaching the soil but should dry out and harden soon afterwards. Indeed, the high amount of precipitation recorded in April-June 2020 in Zaragoza speeded up the completion of the trials.

Despite the mulches showed cracks and signs of degradation (data not shown) they were still capable of controlling weeds to some extent during a certain period. Possibly a gradual transition occurred from the initially higher physical punching resistance to a different way of impeding weeds to germinate, maybe due to the chemical composition of the mulches prior to total degradation and incorporation to the soil.

Overall, in all the trials except the vineyard, some of the tested hydromulches achieved a lower mean weed soil cover than the manually weeded plots. The latter is comparable to mechanical weeding, being the most effective alternative in most situations. It also needs to be stressed that herbicides are selective and do not control all species even in perennial crops where herbicides are often mixed to achieve an all-round control, as e.g. in peach orchards (Buckelew et al. 2018). Indeed, glyphosate-resistant *Conyza* spp. populations have been reported since 2004 (Heap 2024) and are widespread in orchards in Spain, so herbicide use is not completely reliable either. Moreover, in the artichoke trial data presented here, the hydromulches even achieved a lower soil cover of two of the three most frequent weed species than in the herbicide-treated plots.

Possible Drawbacks of Hydromulch for Weed Control

The association of volunteer barley and *Bromus* sp. with WS in the peach trial (Fig. 9) as well as that of *Echinochloa* ssp. with RH demonstrates the need to prevent the introduction of non-desired plants into the hydromulches. Subjecting the rice husk to high temperature to devitalize the seeds was efficient in the Zaragoza trials but is too cost-ineffective; targeted sieving could be a solution, although it is difficult for the case of *Echinochloa* due to the similar size of the rice husk. Another option could be mixing the hydromulch some days before use (except for the gypsum) and storing at mild temperatures, in this way promoting the germination of the seeds in the mulch mixture prior to application.

The irregular results found for the tested hydromulch types regarding the soil cover reduction capacity of perennial weed species suggest that it will not be sufficient to control them with the hydromulches alone when they occur

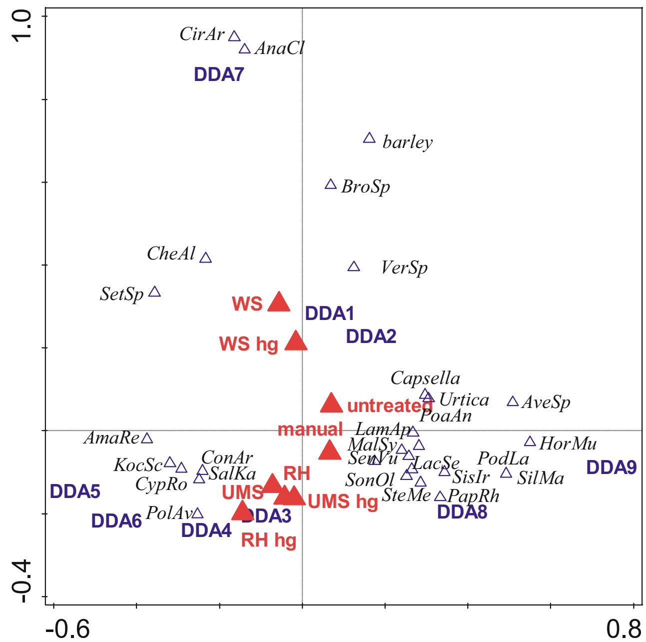


Fig. 9 CCA analysis for the peach trial. Plants are named with the first three letters of the genus and first two of the species

in infestations at high abundance. Additionally, the possibility that wind-dispersed weed species are able to grow on the hydromulches is also a drawback that needs to be studied in further detail. For one of these species (*C. bonariensis*), it has been confirmed experimentally that seeds are spread downwind even as far as 530 m (Bastida et al. 2021), demonstrating that it will be difficult to avoid its presence in areas where this species is frequent. However, RH oil was capable of reducing the mean weed soil cover of *Conyza* sp. compared to RH in the dry part of the almond trial (Fig. 5). Possibly the surface of the mulch impeded the wind-dispersed *Conyza* seeds from establishing, which is another aspect that should be analysed in future.

Another consideration is that the weed control effect lasted around one year. Taking into account that certain herbicides are not allowed in three- to four-year-old plantations, a longer weed control effect would be desirable.

Conclusions

In all four trials annual weeds were better controlled by the tested hydromulches than perennials; however the overall weed control effect lasted statistically significant around one year. Weed cover increased after high rainfall events and wind-dispersed species grew in importance over time. None of the tested hydromulch formulations (WS, RH or UMS) including lower gypsum rate and spraying lineseed oil on the RH mulch did improve the weed control duration significantly.

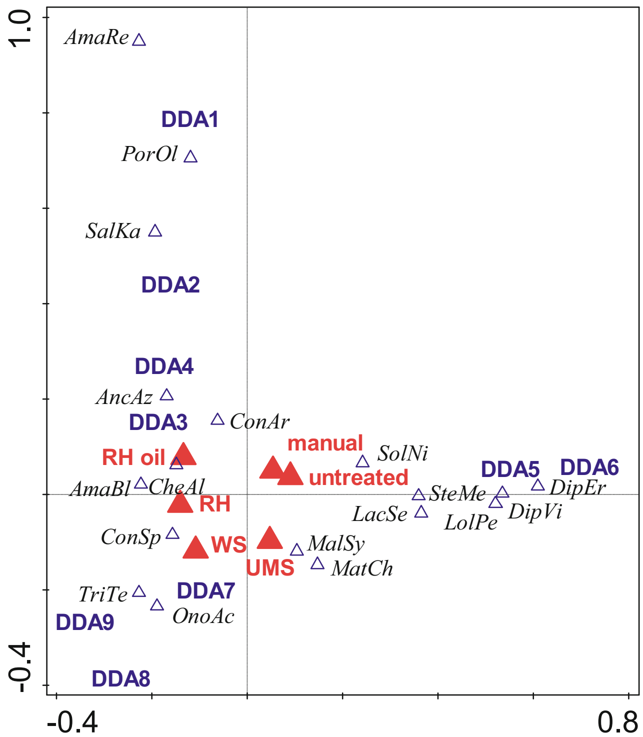


Fig. 10 CCA analysis for the dry part of the almond trial. Plants are named with the first three letters of the genus and first two of the species

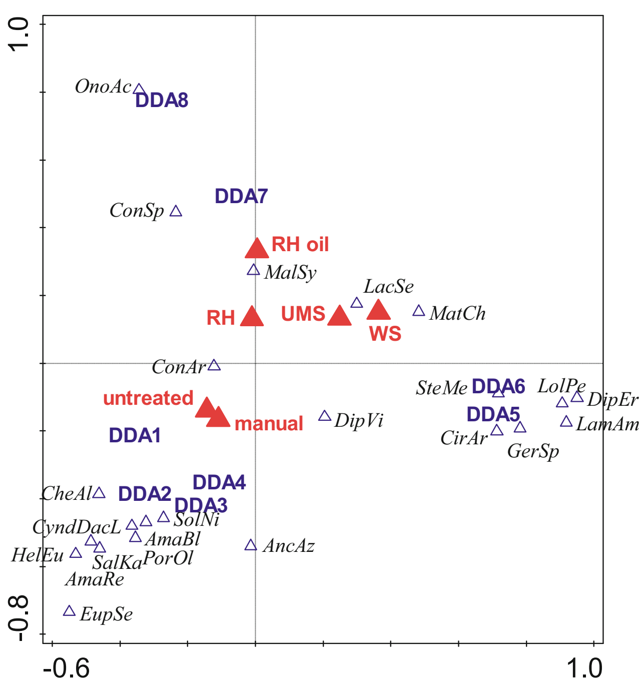


Fig. 11 CCA analysis for the moist part of the almond trial. Plants are named with the first three letters of the genus and first two of the species

For some crops such as artichoque or aromatic plants this weed control period can be sufficient because the crop covers the soil substantially at that time; however, a longer durability can be necessary in other perennial crops with a long lifespan such as vineyards, almond trees, etc. The use of local crop residues for these mulches is potentially an advantage of this technology but the high volume needed might be a drawback for the installation.

If a longer weed reduction is targeted with the hydromulches, further steps could envisage a reapplication after the appearance of the first cracks and following up the mulch performance afterwards. Achieving a more slippery surface to prevent wind-dispersed seeds from establishing could also be targeted as well as searching for additives that allow a faster drying after rainfall. Also, the testing of hydromulches including different lignocellulosic compounds could be interesting for the purpose of finding a good and cheap mixture, as well as the development of an effective mechanical application of the hydromulches.

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Declarations

Conflict of interest A. Cirujeda, J. Pueyo, M.M. Moreno, C. Moreno, J. Villena, J. López-Marín, M. Romero-Muñoz and G. Pardo declare that they have no conflict of interests.

Ethical standards For this article no studies with human participants or animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

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