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The potential of culinary vegetable oils as herbicides in organic farming: the effect of oil type and repeated applications on plant growth

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Abstract This study tested the herbicidal effects of raw and processed culinary oils (rapeseed oil, sunflower oil, olive oil, flax/linseed oils) on nine plant species (poppy, white clover, alyssum, lupin, buckwheat, mustard, oats, perennial ryegrass, tall fescue). Oils were also tested on weeds that naturally emerged from farm soil. Plants were coated with oil using a pressurized hand pump, then maintained in a glasshouse or outdoor plant facility until harvested approximately 5 weeks after oil application. All the oils tested caused a decrease in plant dry matter compared with water-sprayed control treatments, although there was some inconsistency in herbicidal effects among plant species, trials and growing conditions. Spraying plants with rapeseed oil on multiple occasions tended not to be more phytotoxic than only a single spraying. Raw or organic oils were not consistently more phytotoxic than processed versions of the same oil type. There was some evidence that negative effects of oils on plant growth were more apparent under warmer conditions. The results suggest that culinary oils could reduce the biomass of weeds in an environmentally friendly way that is permissible to organic growers. However, the herbicidal activity of these oils appears low, and the quantities required to obtain substantial weed control may not be economically viable in all instances.

Keywords Cooking oil · Olive oil · Rapeseed oil · Sunflower oil · Linseed oil · Flax oil

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Introduction

The highest losses encountered in organic arable and horticultural systems in terms of crop yield or crop quality are due to weeds, which continue to be a major challenge for organic practitioners (Dayan et al. 2009; Liebman and Davis 2009; Kolb and Gallandt 2012; McErlich and Boydston 2013; Cai and Gu 2016). The restrictions on organic producers limit the weed control methods they are permitted to use, especially with respect to highly efficient, cost-effective, synthetic herbicides. Organic weed control often involves a number of complementary approaches, including cultural methods (e.g. crop rotation, high crop sowing density, cover cropping, intercropping, low tillage) and physical or mechanical methods (e.g. mulching, burial, hand weeding, flame weeding, steam injection) (Ascard 1995; Bond and Grundy 2001; Rasmussen 2003; Liebman and Davis 2009; Kolb and Gallandt 2012; McErlich and Boydston 2013; Latify et al. 2017). Additionally, organic practitioners have access to biocontrol methods and 'bioherbicides' developed from fungal plant parasites, soil-borne fungal pathogens, pathogenic

bacteria and plant-parasitic nematodes, although few of these products have been successfully registered and commercialized (Cai and Gu 2016).

An increasing number of products based on natural-substances have been developed as herbicides permissible for use in organic systems. These include products based on allelopathic corn and mustard seed meals, acetic acid ('horticultural vinegar') and fatty acids (ammonium nonanoate; 'herbicidal soaps') (Turk and Tawaha 2003; Dayan et al. 2009; Fogelberg 2009; Cai and Gu 2016). Phytotoxic mixtures, including commercial products, are now being manufactured based on plant-derived essential oils, obtained from an eclectic range of trees and herbs, such as: pine, cypress, cedar, manuka, eucalyptus, clover, clove, lemongrass, cinnamon, mint, rosemary and sage (Tworkoski 2002; Ramezani et al. 2008; Dayan et al. 2009; McErlich and Boydston 2013; O'Sullivan et al. 2015; Cai and Gu 2016; Synowiec et al. 2017). These essential oils, being natural in origin, are generally considered relatively safe to handle and may also represent a lower risk in terms of the development of herbicide resistance when used in mixtures or in rotations (Amri et al. 2013). Compared with synthetic herbicides, there may be additional environmental benefit in using plant-based oils for weed control in that these oils will tend to rapidly biodegrade: lipases are produced by a wide range of microorganisms and metabolic pathways degrading glycerol and fatty acids are virtually ubiquitous (Cornish et al. 1993).

The use of oils as herbicides is long established, but traditionally based on synthetic, petroleum fractions (e.g. gasoline and kerosene) rather than plant-based oils (Gauvritz and Cabanne 1993). The phytotoxicity of oils appears to be positively associated with unsaturation and low molecular weight, and function via mechanisms that inhibit transpiration and photosynthesis due to stomatal penetration or blocking (Tworkoski 2002). Many seed oils (soybean, rapeseed, sunflower, linseed) have been used as adjuvants with synthetic herbicides and found to be as efficient as petroleum based oils in this role (Pannacci et al. 2010; Heini et al. 2012; Izadi-Darbandi et al. 2013). Additionally, the application of emulsions of cooking oils has been shown to reduce infestation of pest insects such as aphids, and fungal pathogens such as powdery mildew (Gan-Mor et al. 2012). However, Tworkoski (2002), based on the results of leaf-disc tests, indicated that basic vegetable oils such as sunflower, rapeseed, flax, grape seed and olive oils, had no direct herbicidal effects against plant. Similarly, Izadi-Darbandi et al. (2013) found that a number of vegetable oils, including rapeseed, soybean, olive and sesame, did not reduce the fresh- and dry-weight of wild oats.

In contrast, herbicides based on essential oils can be very effective and rapidly destroy plant tissue, with visible plant damage occurring less than an hour after spraying (Boyd and Brennan 2006). These products tend to be non-selective, and are more effective when used to control young, broad-leaved, weeds, than against grasses or plants with woody stems. Good coverage is considered essential, so large volumes of product are often required, and, as only contacted leaf material is damaged, re-growth can occur making (multiple) reapplications needed, especially for perennial weeds (Lanini 2010). Often, the costs associated with these products prohibits their use on large scale operations, but they may be viable for use by direct spot spraying, on small scale systems with high-value produce (Dayan et al. 2009; Lanini 2010; McErlich and Boydston 2013).

Previous research suggests that a number of factors appear to influence the phytotoxic effects of foliar oil application. Merfield (2007) observed that application of refined rapeseed oil appeared to cause systemic death of pasture, whereas unrefined organic flax oil caused leaf death but lacked a systemic lethal effect. Also, a number of previous reports have indicated that reapplication of oil-based herbicides is required to maintain weed suppression, and that ambient temperature can influence the herbicidal effects of oil application. To address these issues and, therefore, obtain a fuller picture of the factors potentially influencing the use of oils as weed suppressants, we have (a) screened unprocessed and processed versions of four types of vegetable oil (rapeseed, olive, sunflower and flax) to assess their herbicidal effects on a range of broad-leaved and monocotyledon plants; (b) examined whether applying processed rapeseed oil up to three times had additional inhibitive effects on plant growth compared to just a single application; (c) performed some assays in warm glasshouse conditions and others in a colder outdoor plant growth facility.

Materials and methods

General

Seeds were obtained from King Seeds Ltd., Katikati, NZ, and from The Warehouse, Christchurch, NZ. Nine

plant species, providing a mixture of broad-leaved and monocotyledon plants, were tested in these trials as surrogate weeds: poppy (*Eschscholzia californica* Cham.), white clover (*Trifolium repens* L.), alyssum (*Lobularia maritima* (L.) Desv.), blue lupin (*Lupinus angustifolius* L.), buckwheat (*Fagopyrum esculentum* Moench), mustard (*Sinapis alba* L.), oats (*Avena sativa* L.), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.). All plants used were common garden varieties, and no details regarding plant cultivar or variety were recorded. Although the plants used in the study were selected so that we could test the phytotoxic effects of oils on a representative a range of dicotyledon and monocotyledon species, many of them are also considered as weeds in New Zealand cropping systems (Popay et al. 2010).

All trials were performed at the Horticultural Research Section, Lincoln University, Canterbury, New Zealand. Plants were grown in plastic pots (8 × 8 cm; 10 cm deep) using an in-house potting mix consisting of 80% compost and bark, 20% pumice, with the addition of Osmocote® slow release fertilizer. All plants were lightly watered each day apart from the day on which oils were applied, when watering was not carried out either prior to or after oil application. Seeds were sown directly into pots and thinned down to three plants per pot after 10 days. Oil treatments (see Table 1) were initiated when plants were approximately 3 weeks old and harvested 4–5 weeks later. In some trials, the plants were maintained in a glasshouse facility maintained at 15–25 °C, whereas in other cases plants were maintained in a covered outdoor plant house where temperature ranged from 10 to 20 °C (further details given below).

Table 1 Culinary oils tested for their herbicidal activity in this study

Oil	Vegetable source	Processing status
Lupi extra light olive oil	Olive	Processed
Lupi organic XV olive oil	Olive	Organic/raw
Sunfield sunflower oil	Sunflower	Processed
Ceres organic sunflower oil	Sunflower	Organic/raw
Simply pure canola oil	Rapeseed	Processed
The good oil extra virgin rapeseed oil	Rapeseed	Organic/raw
Amazing haste boiled linseed oil	Flax/Linseed	Processed
Waihi bush organic flax seed oil	Flax/Linseed	Organic/raw

Oils were applied to plants using pump-action kitchen oil sprayers until foliage was showing good coverage. Water was used a control treatment. After spraying, pots were arranged on benches using a semi-randomized/ad hoc design, with care taken to ensure plants were not touching. At harvest, any remaining above-ground foliage was removed using a razor blade, wrapped in tissue, dried in an oven for 3 days at 65 °C, and then weighed.

Rapeseed oil single application trial

The effect of a single application of processed rapeseed oil was used as an initial study to gauge the effects of oil treatment on plant growth. Eight plant species (lupin; poppy, white clover, alyssum, buckwheat, oats; ryegrass, tall fescue) were assessed. Plants were sprayed with oil, maintained in the glasshouse facility, and harvested 4 weeks after spraying. There were between 4 and 10 replicates per treatment for each plant species (see Table 2).

Rapeseed oil multiple application trial

To assess whether plant inhibition might be dose related, a second series of trials was performed where processed rapeseed oil was applied to foliage up to three times, 1 week apart, before harvesting 4 weeks after the initial application. There were 5 replicates per plant per oil treatment. In the multiple rapeseed oil application trials involving oats, alyssum, lupin and mustard the plants were maintained in the outdoor plant house. For the trials involving poppy and clover, the plants were maintained in the glasshouse facility.

Comparison of oil types and processing

In this trial, four different vegetable oils were compared in their herbicidal action: rapeseed, olive, sunflower and flax, and for each vegetable oil, one variety classified as organic or 'raw' and one variety classified as 'processed' was obtained (Table 1). For trials involving, oats, alyssum, lupin and mustard, all eight oils (and a water control, $N = 5$ per treatment) were tested, and the plants were maintained in the outdoor plant facility. For poppy and clover, the rapeseed oils were not available, and in these trials, the plants were maintained in the glasshouse facility.

Table 2 Response of plants to foliar application of rapeseed oil (Simply Pure Canola Oil). Values represent mean (± se) dry weight (mg) per pot, with the exception of natural weed species which indicates mean number of species per pot at the end of the trial. *N*—the number of pots used in each oil treatment and control; *GH*—glasshouse 22 °C; *CR*—cold room 15 °C. *P* values were obtained from unpaired t-tests (single application) and from nested ANOVA (multiple application); means not sharing a letter code were separated as significantly different by Fisher's LSD ($P < 0.05$)

	Species	N	Number of oil applications				P_{Oil}	P_{Dose}
			0	1	2	3		
GH	Clover #1	7	330 ± 57	101 ± 35	–	–	0.007	
GH	Poppy #1	6	191 ± 25	66 ± 8	–	–	0.007	
GH	Alyssum #1	7	199 ± 26	137 ± 13	–	–	0.068	
GH	Lupin #1	4	719 ± 87	156 ± 24	–	–	0.008	
GH	Oats #1	4	1404 ± 111	122 ± 72	–	–	< 0.001	
GH	Buckwheat	7	75 ± 13	59 ± 12	–	–	0.364	
GH	Festuca	7	170 ± 27	117 ± 22	–	–	0.157	
GH	Ryegrass	10	64 ± 11	22 ± 2	–	–	< 0.001	
GH	Clover #2	5	230 ± 76 ^{a}	119 ± 45 ^{ab}	84 ± 23 ^{b}	86 ± 10 ^{b}	0.023	0.836
GH	Poppy #2	5	1421 ± 133 ^{a}	258 ± 78 ^{b}	352 ± 63 ^{b}	261 ± 82 ^{b}	< 0.001	0.725
CR	Alyssum #2	5	244 ± 34 ^{a}	60 ± 23 ^{b}	23 ± 15 ^{b}	22 ± 12 ^{b}	< 0.001	0.433
CR	Lupin #2	5	610 ± 56 ^{ab}	570 ± 60 ^{ab}	458 ± 44 ^{a}	634 ± 55 ^{b}	0.378	0.097
CR	Oats #2	5	754 ± 31 ^{a}	692 ± 90 ^{a}	701 ± 37 ^{a}	1041 ± 99 ^{b}	0.496	0.004
CR	Mustard	5	1286 ± 115 ^{a}	1079 ± 54 ^{a}	682 ± 37 ^{b}	532 ± 66 ^{b}	< 0.001	< 0.001
GH	Natural weeds: dry weight (mg)	15	310 ± 24 ^{a}	155 ± 35 ^{b}	156 ± 20 ^{b}	175 ± 22 ^{b}	< 0.001	0.776
GH	Natural weeds: species	15	3.15 ± 0.24 ^{a}	2.25 ± 0.37 ^{b}	2.50 ± 0.27 ^{b}	2.56 ± 0.29 ^{b}	< 0.001	0.821

The effect of oils on weeds emerging from field soil

To gain information on how the application of oils could suppress a more diverse array of naturally-occurring weeds, surface soil was collected from the organic farm at The Biological Husbandry Unit, Lincoln University, New Zealand. The soil was placed into plastic pots (8 × 8 cm; 10 cm deep), watered, and weed seeds allowed to germinate. After 3 weeks, any pots that exhibited no seedling emergence were removed from the study, and the remaining pots allocated to various oil spraying treatments, including multiple rapeseed oil applications ($N = 15$), and the testing of different organic and processed vegetable oils (flax, sunflower, olive; *N* ranged from 7 to 12 pots per treatment group). To achieve a good estimate of background weed growth, 26 pots were assigned to an untreated group which acted as a control treatment. The pots were maintained in the glasshouse facility. Four weeks after spraying, the existing weeds in each pot were identified to species, separated, dried and weighed.

Statistical analysis

All statistical analyses were performed using Genstat software (v15; VSN International, UK). For the single rapeseed oil applications, the dry matter obtained from the oil treated and control plants was compared using an unpaired t-test with degrees of freedom adjusted depending on the degree of variance inequality.

The oil comparison experiments consisted of a factorial design (oil type × processing status) with the addition of no-oil control treatment (Piepho et al. 2006; Onofri et al. 2010). Thus, the dry matter obtained from the various treatments was compared using ANOVA models with a nested design that incorporated overall treatment (oil *v* no oil), oil processing status (processed *v* raw) and oil type (sunflower, olive, rapeseed, flax) as explanatory factors. For the rapeseed oil multiple application experiments, the nested ANOVA models used to compare dry weight included treatment (oil *v* no oil) and applications (0, 1, 2 and 3) as explanatory factors. For the natural weed emergence trials the data regarding number of

extant weed species and total dry weight at harvest were also analyzed using nested ANOVA models. In all cases, the required degree of normality of errors and equality of group variances was considered acceptable after visual inspection of the residuals obtained from the ANOVA (Kozak and Piepho 2018).

Individual oil treatments were compared to the control group using unprotected Fisher's least significant differences (LSDs; $P < 0.05$). There is much debate over the use and validity of multiple comparison procedures, and the unprotected LSD does not make adjustments for increasing likelihood of Type I errors as a function of the number of pairwise comparisons that are performed. However, because our aim was to identify any treatments that may warrant further study with regard to their herbicidal effects, and because using more conservative post hoc tests such as Tukeys HSD test could lead to Type II errors, we have chosen to use the unprotected LSD because of its consistency (Onofri et al. 2010; Saville 2015).

For ease of comparison among plant species, the results of the multiple oils trials have been presented as relative DM compared to the mean DM in the control treatment. The DM for each replicate was first transformed as relative DM (%) = [actual DM/mean control DM] × 100%, and then mean and standard errors calculated from these transformed data.

Results

Rapeseed oil: single and multiple applications

In the rapeseed oil single application trials, the oil treatment caused a reduction in average DM in all cases (Table 2). Oats was the plant species most severely inhibited by the oil, with a DM at harvest of less than 10% than of the control. Clover, lupin, poppy and ryegrass were also inhibited; the DM of the oil-treated plants being approximately 1/3 of that which occurred in the controls. Buckwheat was the least affected species, the rapeseed oil causing only a 21% reduction in DM (Table 2).

In the multiple application rapeseed oil trials, poppy and alyssum were significantly inhibited after just one application, whereas the DM of clover and mustard were reduced compared to the control treatment after two applications (Table 2). Lupin and oats were not affected by the application of the rapeseed oil compared to the control, although there was some evidence of differences among the oil treatments (Table 2).

Comparison of oil types and processing status

For clover and poppy, there was a highly significant ($P < 0.001$) reduction in plant DM caused by the application of oil: the overall DM in treated plants was only 24% of that observed in the control treatment for poppy, and 32% for clover (Fig. 1a, b). However, there was no effect of processing status of the oil, or individual oil types for either plant species.

For alyssum, there was an overall reduction in DM (28% of the control DM) caused by applying oil ($P < 0.001$) (Fig. 1c). There was no effect of processing status ($P = 0.121$) on alyssum DM, but the three-way interaction term between oil treatment, processing status and oil type was significant ($P = 0.032$), indicating the extent of the reduction in DM was dependent upon the actual oil used. The flax oils caused the greatest reduction in DM of alyssum, with the organic flax oil completely eradicating the plants from every replicate.

For mustard, DM was reduced in the oil-treated plants to 70% of that seen in the control group, and there were statistically significant effects related to overall oil treatment ($P < 0.001$), processing status of the oil ($P = 0.004$) and oil type ($P = 0.002$) (Fig. 1d). The processed rapeseed oil and sunflower oil treatments did not significantly reduce DM compared to the control, and therefore, the application of the organic oils resulted in a more severe reduction in DM (63% of control DM) compared with the processed oils (76% of the control DM).

For oats and lupin, the application of oils caused no statistically significant overall reduction DM (lupin 98% control DM, $P = 0.848$; oats 98% control DM, $P = 0.872$) (Fig. 1e, f). Only one individual oil treatment, the processed olive oil, was identified by the unprotected LSD as producing reduced DM in lupin.

The effect of oils on weeds emerging from field collected soil

Twenty species of plants were recorded at harvest in the pots containing soils collected from the organic farm (Appendix 1 and Appendix 2). The dominant plant species, in terms of DM in the control pots, were *Daucus carota, Lactuca sativa*, *Lolium perenne*, *Fumaria officinalis*, *Veronica persica*, *Capsella bursa pastoris, Plantago lanceolata* and *Trifolium repens*. In the rapeseed oil trials, the total DM and species richness per pot were both significantly decreased by the processed rapeseed oil

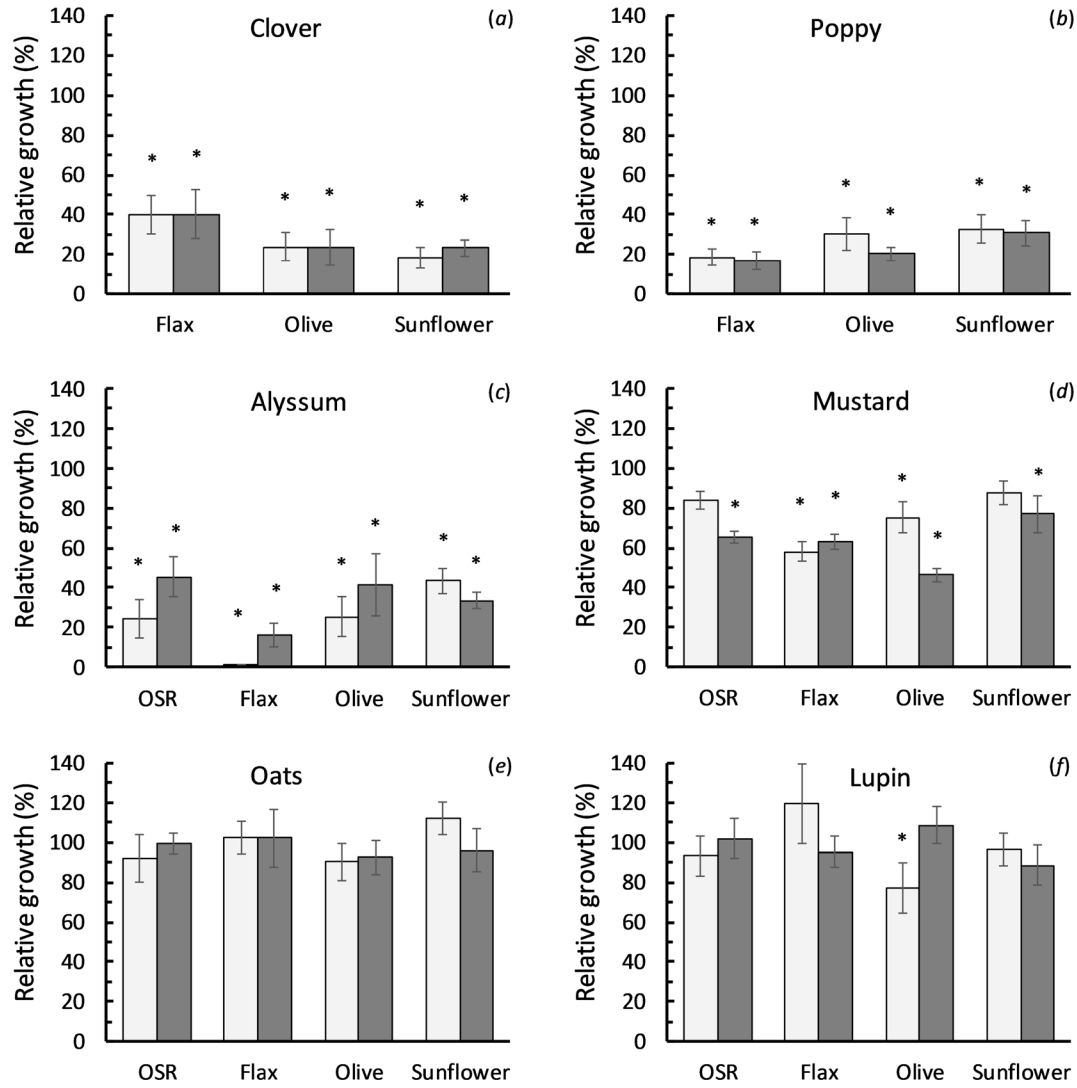

Fig. 1 Response of plants to foliar application of different culinary vegetable oils: flax, olive, sunflower and rapeseed oil (OSR). Light gray bars—processed oils; Dark gray bars—raw/organic oils. Clover and poppy trials were run in a glasshouse with temperature 15–25 °C. Remaining plant trials were run in covered outdoor facility with temperature 10–20 °C. Values presented are mean (± se) relative dry weight (%) compared to control treatment. *Indicates separation from control treatment by Fisher's unprotected LSD ($P < 0.05$)

but this was not dose related, reductions being observed after one, two and three applications (Table 2).

In the oil type trial, there was a strong reduction in species number due to the application of oil of any kind ($P < 0.001$): both the processed and organic flax oils, the organic olive oil and processed sunflower oil caused significant reductions in species number (by approximately one species per pot on average) compared to the control pots (Fig. 2a). However, the processing status of the oil ($P = 0.991$) and the types of oil ($P = 0.638$) did not significantly influence the number of surviving weed species (Fig. 2a).

There was an overall significant reduction in DM due to oil application ($P < 0.001$), and the nested ANOVA suggested there was moderate evidence of differences in the potencies of the different oils ($P = 0.053$), but not their processing status ($P = 0.193$) (Fig. 2b). Both the processed and organic olive oils and the processed sunflower oil significantly reduced DM compared to that which occurred in the control pots (Fig. 2b).

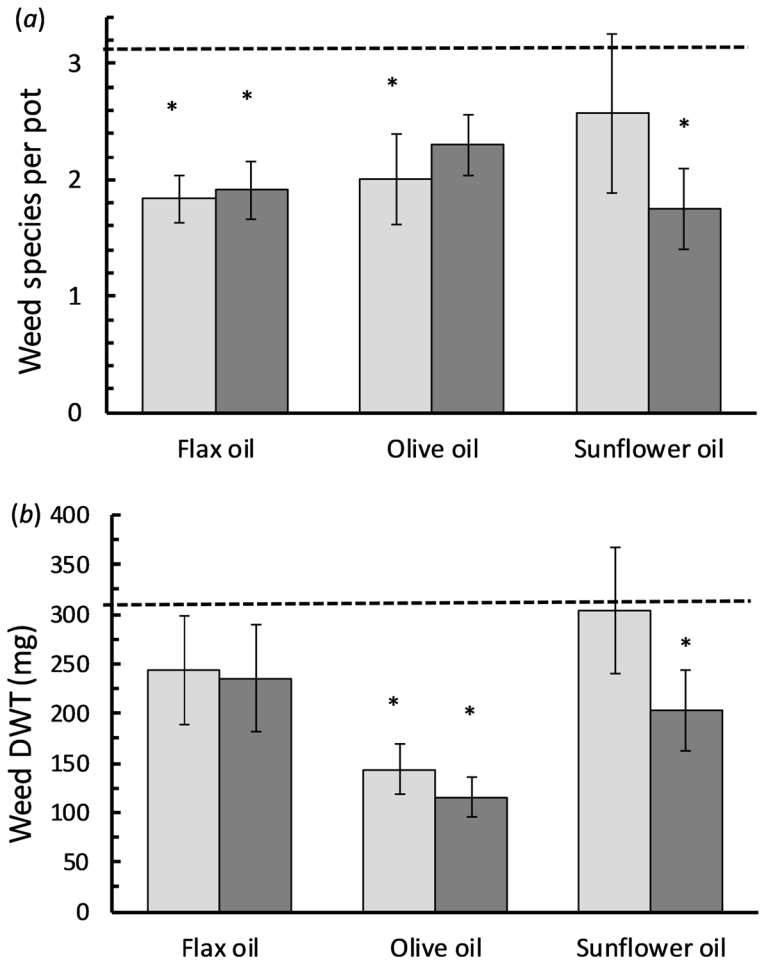

Fig. 2 Response of naturally emerging weeds to foliar application of different culinary vegetable oils (light gray—processed oils; dark gray—raw/organic oils). Values presented are mean per pot (± se) of **a** number of weed species and **b** total dry weight (mg) at final harvest. Dotted horizontal lines indicate mean control value and * indicates separation from control treatment by Fisher's unprotected LSD ($P < 0.05$)

Discussion

The effect of culinary oils on DM accumulation in plants

The results of these trials suggest that culinary vegetable oils inhibit growth of dicotyledonous and monocotyledonous plants. However, the phytotoxic activity of these oils appears low, and the usual caveats regarding organic herbicides listed by Lanini (2010), such as cost, repeated applications, and thorough coverage, will also apply to the use of culinary oils in a field setting. Our results indicate that there is no requirement to use relatively expensive organic or unprocessed oils when evaluating phytotoxicity of culinary oils, as the cheapest oil tested—processed rapeseed oil—proved effective. There may be potential to cheaply obtain sufficient volumes of used cooking oil from hotels, restaurants and food outlets, already familiar with providing oil for conversion to biodiesel, which would enable coverage of considerable areas. Coverage could be extended if the oils are emulsified with water or diluted with chemical 'thinners'. However, the use of water-diluted emulsified cooking oils for plant protection against insect pests and pathogens is known to render oils non-phytotoxic (Gan-Mor et al. 2012), so this route may not be open for oils intended for herbicide use.

Our results disagree with those presented by Tworkoski (2002), who found that basic vegetable oils such as sunflower, rapeseed, flax, and olive oils, had no direct herbicidal effects against plants. However, those results were obtained during a screening test of different oil types involving leaf-discs, and not on the effects of oils against whole plants. Izadi-Darbandi et al. (2013) applied nine different seed oils to wild oats (*Avena ludoviciana* L.) but reported that only application of cotton seed oil resulted in significant reduction in dry weight. It is possible the emulsified oils used in that study reduced the phytotoxicity of the oils, or that wild

oats is particularly resistant to oil application, as some of the oils they tested inhibited plant growth in our experiments (e.g. rapeseed oil/canola oil, olive oil). In our trials with common oats (*Avena sativa* L.), the plants were severely inhibited in the single application rapeseed oil trial but were not inhibited by oil application in the second set of trials. The somewhat spurious finding that oats and lupin appeared to gain DM after being sprayed three times with rapeseed oil requires some speculation. The plants in these treatments looked very unhealthy at the time of harvest and the high DM values obtained were unexpected. It is possible that oil residues on the leaves, due to the high quantities of oil sprayed onto these plants, somehow contributed to the measured DM, although this possibility would probably not account for all of the extra DM, and this phenomenon was not observed in other trials. For oats, an additional possibility is that the application of oil had killed off the exposed leaves and encouraged the rapid growth of fresh shoots.

The influence of temperature on the phytotoxic effects of culinary oils

Previous studies have suggested that the action of organic herbicides, including those based on plant-derived essential oils, is enhanced in warmer temperatures (Lanini 2010; McErlich and Boydston 2013). Overall, significant reductions in plant DM were observed in oil treated plants maintained both in the glasshouse (15–25 °C) and in the outdoor plant facility (10–20 °C). Conversely, statistically non-significant effects were obtained in the warmer glasshouse (rapeseed oil *v* buckwheat, festuca) as well as the cooler outdoor plant house (oats and lupin). However, the results for lupin and oats indicated there may have been an effect of temperature: both species were severely inhibited when rapeseed oil was applied under warm glasshouse conditions but showed no significant response when the oils were applied outdoors. No trials were performed to simultaneously assess the effects of the same oils on the same plant species under different temperature (and sunlight) regimes, and this aspect requires further attention.

Experimental and statistical considerations

Although the results in terms of statistically significant reductions in plant dry matter appeared variable, a more general look at the data suggests the inhibitory effects of oil application were actually fairly consistent. For example, for the single species trials, a single application of rapeseed oil produced a reduction in mean DM compared to the control in all 14 cases (Table 2). That some of these reductions in DM were not statistically significant is likely due to a combination of no actual effect (i.e. the null hypothesis is true), along with high within-treatment variability and small sample sizes that resulted in low statistical power of detection (Ellis 2010). For example, in the Clover #2 trial, a single rapeseed oil application resulted in an average DM reduction of just under 50% but this was not clearly separated from the control treatment by the unprotected LSD. Although retrospective power analysis is not directly useful in our case, it does to help to guide future studies on this system. The Clover #2 control, with a mean DM of 230 mg per pot and SD of 170 mg, had a relatively high CV% of ≈ 74% compared to other treatments. Based on this level of variation, if we are aiming to identify fairly substantial herbicide-induced reductions in DM of 50% as statistically significant, then a sample size ≥ 35 per treatment would be required to provide adequate power of detection (≥ 80%) at the standard level of significance ($P = 0.05$).

Plant dry matter at harvest is a standard measure of herbicide efficacy. However, for growers who have low tolerance of weeds due to the low competitiveness of vegetable crops, the key metric of herbicide efficacy is weed mortality. In experiments such as these, however, dry matter is often unable to distinguish between dead and live plants, as plants that have been killed by a treatment will not have decayed within the time frame of the study. At the same time, weeds that have not been killed but have suffered a significant check in their growth may lose their competitive advantage against the crop, and, even though they have not been killed, their harmfulness to the crop will have been eliminated or at least considerably reduced. It is therefore recommended that, in future research, both dry matter and plant mortality are used as measures of weed suppression.

Another problem associated with the use of DM as a measure of herbicide success was revealed when assessing the impact of oils on the weeds that naturally germinated from the farm soil. Significant reductions in species number and total DM were observed in the oil treated pots at harvest, providing further support that these substances may have potential to reduce weed diversity and biomass in a field setting. However,

problems arose when trying to assess the impact of the oils on individual weed species, as some weed species did not occur in the controls. In this trial, pots were assigned to treatments at random and the control treatment was well replicated ($N = 26$). However, when species did not appear in the controls but did appear in oil treatments there arose the doubtful conclusion of a positive association between plant biomass and herbicide application.

Conclusions

We accept that these trials represent a preliminary examination of the herbicidal effects of vegetable oils, and that some aspects of the study were not ideal. For example, we have adopted a foliage 'saturation' method for oil application, analogous to spraying to 'run off' in insecticide and fungicide trials, and thus have no real measure of the actual amount of oil that was applied, both in terms of total mass or volume and in terms of oil per unit area of foliage. Also, the overall trial scheme was not orthogonal, in that all plants were not tested with all oil types, and not all oil/plant combinations were tested under both glasshouse and outdoor conditions.

From a practical point of view, the unit cost of the oils and the quantities required to obtain substantial weed control may not be economically viable for all growers, and, as many organic certification schemes require the minimum processing of products, some leeway may have to be found when using processed oils as herbicides rather than for culinary use. However, overall, our study demonstrates that application of culinary oils can reduce weed biomass in a way that is likely acceptable to organic growers, and thus these methods, once developed, have potential to be incorporated into a 'many hammers' approach to weed management in organic production systems.

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Appendix 1

Table 3 Weed species occurring in naturally-obtained soils after spraying seedlings with processed rapeseed oil. Mean dry weight (mg) per pot at harvest

Family	Species	Number of oil applications			
		0	1	2	3
Amaranthaceae	*Chenopodium album* L.	1.81	0.50	0.00	0.00
Apiaceae	*Daucus carota* L.	39.73	14.81	5.69	0.00
Asteraceae	*Lactuca sativa* L.	38.00	21.75	6.81	0.00
Asteraceae	*Taraxacum officinale* L.	15.38	6.75	19.88	0.00
Brassicaceae	*Capsella bursa pastoris* (L.) Medik.	29.42	3.31	7.75	10.25
Brassicaceae	*Coronopus didymus* L.	0.42	0.00	0.00	4.63
Caryophyllaceae	*Spergula arvensis* L.	0.00	14.00	5.56	10.94
Caryophyllaceae	*Stellaria media* (L.) Vill.	0.00	0.00	3.69	5.00
Fabaceae	*Trifolium repens* L.	21.69	0.00	0.00	0.00
Myrsinoideae	*Anagallis arvensis* L.	21.12	0.00	4.75	4.25
Papaveraceae	*Fumaria officinalis* L.	31.73	39.00	25.44	41.94
Plantaginaceae	*Plantago lanceolata* L.	30.19	5.31	0.00	7.75
Plantaginaceae	*Veronica persica* Poir.	26.12	40.75	58.44	47.63
Poaceae	*Lolium perenne* L.	37.40	7.06	12.31	32.19
Polygonaceae	*Polygonaceae sp*	0.00	0.00	0.00	9.81

Table 3 (continued)

Family	Species	Number of oil applications			
		0	1	2	3
Rosaceae	*Aphanes arvensis* L.	3.12	1.88	2.50	0.00
Solanaceae	*Solanum nigrum* L.	0.00	0.00	1.31	0.00
Violaceae	*Viola arvensis* Murray	13.42	0.00	2.25	1.00
	Total weed dry weight (mg)	309.60	155.10	156.40	175.40
	Mean species per pot	3.15	2.25	2.50	2.56

Appendix 2

Table 4 Mean dry weight (mg) of weed species occurring in naturally obtained soils at end of trial after spraying seedlings with various culinary oils [org - organic; proc. - processed]

Species	Control	Flax (org.)	Flax (proc.)	Sunflower (org.)	Sunflower proc.)	Olive (org.)	Olive (proc.)
Chenopodium album	1.81	0.00	0.00	0.00	0.00	1.58	0.00
Daucus carota	39.73	0.00	8.91	23.43	0.00	8.58	0.00
Lactuca sativa	38.00	73.92	17.27	80.86	0.00	18.92	9.70
Taraxacum officinale	15.38	26.08	20.18	26.57	3.17	15.67	6.10
Capsella bursa pastoris	29.42	0.00	15.18	0.00	4.67	4.50	0.00
Coronopus didymus	0.42	2.17	0.00	0.00	0.00	0.00	1.70
Raphanus raphanistrum L.	0.00	0.00	7.64	0.00	0.00	0.00	0.00
Cerastium fontanum Baumg.	0.00	0.00	0.00	0.00	12.92	0.00	0.00
Spergula arvensis	0.00	23.58	24.91	54.14	70.67	14.17	24.50
Stellaria media	0.00	11.92	18.00	0.00	0.00	0.00	8.40
Trifolium repens	21.69	0.00	0.00	0.00	0.00	0.00	0.00
Anagallis arvensis	21.12	28.33	0.00	21.43	0.00	0.00	0.00
Fumaria officinalis	31.73	0.00	31.18	2.71	4.67	10.33	15.40
Plantago lanceolata	26.12	0.00	32.55	0.00	0.00	0.00	7.50
Veronica persica	30.19	55.42	53.27	76.71	67.33	60.67	22.30
Lolium perenne	37.40	15.92	4.91	9.14	20.08	9.08	18.60
Aphanes arvensis	3.12	0.00	0.00	0.00	9.17	0.00	0.00
Solanum nigrum	0.00	0.00	0.00	3.00	11.00	0.00	0.90
Viola arvensis	13.42	6.42	1.09	5.43	0.00	0.00	0.00
Total weed dry weight per pot	309.50	243.70	235.10	303.40	203.70	143.50	115.10
Species per pot	3.15	1.83	1.91	2.57	1.75	2.00	2.30

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