The potential use of culinary vegetable oils as herbicides: the effect of oil processing and repeated applications on plant growth

Simon Hodge[1,2]*, Charles N Merfield[1], Arthur Bluon[1], Nadine A Berry[2], Dean M O'Connell[1]

1 - Future Farming Centre, Lincoln University, Canterbury, New Zealand.

2 - Faculty of Agriculture and Life Sciences, Lincoln University, Canterbury, New Zealand.

* - author for correspondence: simon.hodge@bhu.org.nz

Key words: cooking oil; olive oil; rapeseed oil; sunflower oil; linseed oil; flax oil; organic farming

Running head: Culinary oils as organic weed control agents.

Word count: 5860

Summary

This study tested the herbicidal effects of raw and processed culinary or house-hold 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) that are potential weeds in the Canterbury region of New Zealand. Oils were also tested on weeds that had naturally emerged from farm soil. Oils were sprayed onto foliage of potted plants using a pressurized hand pump, and the plants maintained either in a glasshouse or outdoor plant facility until harvest approximately 5 weeks after oil application. All the oils tested caused a decrease in plant dry matter, compared to water-sprayed control treatments, in some cases. 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 more phytotoxic than processed versions of the same oil type. The naturally emerging weeds were significantly inhibited either in terms of dry matter or species richness by all of the oils tested except processed sunflower oil. Although the magnitude of oil-induced inhibition was variable among the oils and plant species, and there was inconsistency between the effects observed in the warm glasshouse and cooler outdoor area, the results suggest that culinary oils may have potential to reduce the biomass of weeds in an environmentally-friendly way that is permissible to organic growers.

Introduction

The highest losses encountered by organic practitioners in terms of crop yield or quality are from weeds, and weed management and control which continues to be a major challenge for organic farmers (Dayan et al. 2009; Liebman & Davis 2009; McErlich & Boydston 2013; Cai & Gu 2016). The restrictions placed on organic producers limits the weed control methods they are permitted to use, especially with respect to the application of highly efficient, cost effective synthetic herbicides. Organic weed control often involves a range of complementary approaches, including cultural methods such as crop rotation, high crop sowing density, cover cropping, intercropping and low tillage, and physical or mechanical methods such as mulching, burial, hand weeding, flame weeding and steam injection (Ascard 1995; Rasmussen 2003. Liebman & Davis 2009; McErlich & Boydston 2013). In addition to the above weed management tools, organic practioners also have access to biocontrol methods. Bioherbicides have been 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 & Gu 2016).

An increasing number of products based on natural-substances have been developed as herbicides that are permissible for use in organic systems. These include products based on allelopathic corn and mustard seed meals, acetic acid ('horticultural vinegar') and fatty acids and their salts (ammonium nonanoate; 'herbicidal soaps') (Turk & Tawaka 2003; Dayan et al. 2009; Fogelberg 2009; Cai & Gu 2016). An increasing number of phytotoxic mixtures, including a widening range of commercial products, are being produced based on plant-derived essential oils, obtained from an eclectic range of trees and herbs, such as: pine, cypruss, cedar, manuka, eucalyptus, red clover, clove, lemongrass, cinnamon, mint, rosemary and sage (Tworkoski 2002; Ramezani et al. 2008; Dayan et al. 2009; McErlich & Boydston 2013; Cai & Gu 2016; Synowiec et al. 2017). These essential oils, being natural in origin, are generally considered to be relatively safe for people and less damaging to the environment compared with synthetic herbicides, and may also represent a lower risk in terms of the development of herbicide resistance, especially if used in mixtures or in rotations (Amri et al. 2013).

Herbicides based on essential oils can be very effective and rapidly destroy plant tissue, with visible plant damage occurring less than 1 hour after spraying (Boyd & Brennan 2006). However, these products tend to be non-selective, requiring contact with leaf tissue, and are more effective when used to control young, broadleaved, 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 heir use on large scale operations, but maybe considered viable for use as a direct application product, or spot spraying, on small scale systems, with high-value produce (Dayan et al. 2009; Lanini 2010; McErlich & Boydston 2013).

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 (Gauvrit & 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, rape, sunflower, linseed) have been used as adjuvants with synthetic herbicides and found to be as efficient as petroleum based oils (Pannacci et al; 2010; Heini et al. 2012; IzadiDarbandi 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. 2010). There is an additional benefit that vegetable oils biodegrade rapidly: lipases are produced by a wide range of microorganisms and metabolic pathways degrading glycerol and fatty acids are virtually ubiquitous (Cornish et al 1993). However, Tworkoski (2002) indicated that basic vegetable oils such as sunflower, rape, flax, grape seed and olive oils, had no direct herbicidal effects against plants, based on the results of a leaf-disc test. Similarly, Izadi-Darbandi et al. (2013) found that a number of vegetable oils - including oilseed rape, soybean, olive and sesame - did not reduce the fresh- and dry-weight of wild oats

The objective of this study was to re-examine a number of aspects of the herbicidal potential of culinary vegetable oils. The processing of vegetable oils removes or modifies xyz, so it can be hypothesized that potential raw/organic or unprocessed oils may be more potent than their processed counterparts. Therefore we have screened unprocessed and processed versions of four types of vegetable oil (oilseed rape, olive, sunflower and flax) for their effects on a number of broadleaf and monocot plants. Also, as a number of reports indicate that reapplication of bioherbicides is often required to maintain weed suppression, we have examined how applying one oil (processed oilseed rape) up to three times (in three weeks) affects weed dry matter accumulation.

Materials & Methods

General

Seeds for experiments were obtained from King Seeds Ltd., Katikati, NZ, or from The Warehouse, Christchurch, NZ. Nine plant species, providing a mixture of broadleaf and monocot plants that are considered weeds in certain situations in New Zealand, were tested in these trials: 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 in trials were common garden varieties or designed to provide ground cover, and no details regarding plant cultivar or variety were recorded.

105 All trials were performed at in the Horticultural Research Section of Lincoln University,
106 Canterbury, New Zealand. Plants were grown in plastic pots (8 x 8 cm square; 10 cm deep) using a
107 potting mix consisting of 80% compost and bark, 20% pumice, with Osmocote® slow release
108 fertilizer. All plants were lightly watered each day apart from the day on which oils were applied,
109 when watering was not carried out either prior to or after oil application. Seeds were sown directly
110 into pots and thinned down to three plants per pot after 10 days. Oil treatments were initiated when
111 plants were approximately three weeks old and harvested four-five weeks later. In some trials the
112 plants were maintained in a glasshouse facility maintained at 15-25^{o}C, whereas in some cases plants
113 were maintained in a covered outdoor plant house where temperature ranged from 10-20^{o}C.

114 Oils were applied to plants using pump-action kitchen oil sprayers until foliage was showing a
115 good coverage of droplets. Water was used a control treatment. After spraying, pots were arranged on
116 benches using a randomized design, with care taken to ensure plants were not touching. At harvest,
117 any remaining above-ground foliage was removed using a razor blade, wrapped in tissue, dried in an
118 oven for three days at 65^{o}C, and then weighed.

119

120 *Oilseed rape oil: single and multiple applications*

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

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

132

133 *Comparison of oil types and processing*

134 Four different vegetable oils were compared in their herbicidal action: oilseed rape, olive,
135 sunflower and flax. For each vegetable oil, one variety classified as organic or 'raw' and one variety
136 classified as 'processed' were obtained (Table 1). For trials involving, oats, alyssum, lupin and
137 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 the trials involving, poppy and clover, the oilseed rape oils were not included, and the plants maintained in the glasshouse facility.

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 x 8 cm square; 10 cm deep), watered, and weed seeds allowed to germinate. After three 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 oilseed rape applications (N = 15), and the testing of different organic and processed vegetable oils (flax, sunflower, olive; N ≈ 10). To achieve a good estimate of background weed growth, 26 pots were assigned to an untreated group which acted as a control treatment for both the oil variety trial and multiple oilseed rape oil trial. 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 oilseed rape oil applications, the two treatments were compared using an unpaired t-test with degrees of freedom adjusted depending on the degree of variance inequality.

The oil comparison experiments involved a factorial design (oil type x processing status) with the addition of no-oil control treatment (Piepho et al. 2006; Onofri et al. 2010). Thus, the ANOVA models for these experiments consisted of a nested design that incorporated overall treatment (oil *v* no oil), processing status (processed *v* raw) and type (sunflower, olive, oilseed rape, flax) as explanatory factors. For the oilseed rape multiple application experiments the nested ANOVA models included treatment (oil *v* no oil) and applications (0, 1, 2 and 3) as explanatory factors. For the natural weed emergence trials the number of extant weed species and total dry weight at harvest was also assessed 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 after the ANOVA had been performed.

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 the number of comparisons made in relation to the increasing likelihood of Type I errors. 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 a Type II error, we have chosen to use this metric to compare treatments because of its consistency (Onofri et al. 2010; Saville 2015).

Results in 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] x 100%, and then mean and standard errors calculated from these transformed data.

Results

Oilseed rape oil: single and multiple applications

In the eight oilseed rape 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 plant species, the oilseed rape oil causing only a 21% reduction in DM (Table 2).

In the multiple application oilseed rape oil trial, 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). Overall, lupin and oats were not affected by the application of the oilseed rape oil compared to the control, although there was some evidence of differences between the oil treatments. For both of these plant species, and especially lupin, the highest DM was recorded in the three-application treatment (Table 2).

Comparison of oil types and processing

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 (Figure 1a & 1b). However, there was 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 ($P < 0.001$) (Figure 1c). There was no effect of processing status ($P = 0.121$) on alyssum DM, 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 ($P = 0.002$) (Figure 1d). The processed oilseed rape oil and sunflower oil treatments did not significantly reduce DM compared to the control, and therefore the application of the organic oils resulted a more severe reduction in DM (63% of control DM) compared to 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, $P = 0.872$) (Figure 1e & 1f). Only one individual oil treatment, the processed olive oil, was indicated as having reduced DM (in lupin) by the unprotected LSD.

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 (Appendices). 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 oilseed rape trials, the total DM and species richness per pot were both significantly decreased by the processed oilseed rape oil but this was not dose related, reductions being observed after one, two and three applications of oil (Table 2).

In the oil type trial, there was an overall significant reduction in DM due to oil application ($P<0.001$) but not due to processing status ($P = 0.193$). The nested ANOVA suggested there was some evidence to indicate differences in the potencies of the different oils to reduce DM ($P = 0.053$): both of the olive oils and the processed sunflower oil significantly reduced DM compared to that which occurred in the control pots (Figure 2a). In terms of the number of species remaining in each pot at the end of the trial, there was a strong reduction in species number due to the application of oil of any kind ($P < 0.001$). However, processing status of the oil ($P = 0.991$) and the individual types of oil ($P = 0.638$) did not cause significant differences in species number (Figure 2b). In terms of individual oil treatments, both flax oils, the organic olive oil and processed sunflower oil caused significant reductions in species number compared to the control pots (Figure 2).

Discussion

The effect of culinary oils on DM accumulation in plants

In this study, the foliar application of a number of culinary oils caused significant reductions in plant biomass in a number of potential weed species. Reductions in plant growth relative to a water-treated control treatment were observed in both broadleaf and monocot plant species, and were caused by both processed and organic oil types. The results disagree with those presented by Tworkoski (2002), who found that basic vegetable oils such as sunflower, rape, 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) who applied nine different seed oils to oats and reported that only cotton seed oil produced a reduction in dry weight. In our trials, oats severely inhibited in the single application rapeseed oil trial but was 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 oilseed rape 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 was not observed in other plant species. 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 form the growing points.

The influence of temperature on the phytotoxic effects of culinary oils

Previous studies have indicated that the action of organic herbicides, including those based on plant-derived essential oils, is enhanced in warmer temperatures compared to cold conditions (Lanini 2010; McErlich & Boydston 2013). The results for lupin and oats indicated that there may be an effect of temperature: both species were severely inhibited when canola was applied under warm glasshouse conditions but showed no significant response when the oils was applied outdoors. However, overall, significant reductions in plant DM were observed in oil treated plants maintained both in the glasshouse (15-25^{o}C) and in the outdoor plant facility (10-20^{o}C). Conversely, statistically non-significant effects were obtained in the warmer glasshouse (oilseed rape *v* buckwheat, festuca) as well as the cooler outdoor plant house (oats and lupin). 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 dry matter production may appear variable, a more general look at the data actually suggests the inhibitory effects of culinary oil application were actually fairly consistent. For example, for the single species trials, a single application of oilseed rape 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 due to a combination of there being no effect (i.e. the null hypothesis is true), along with high variability and small sample sizes that resulted in low statistical power of detection (Ellis 2010). In the Clover #2 trial, a single oilseed rape oil application resulted in DM reduction of just under 50% but this was not clearly separated from the control treatment by the unprotected LSD. Although retrospective power analysis may not be 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 herbicide-induced reductions in DM of 50% as statistically significant, then a sample size ≥ 35 per treatment is required to provide adequate power of detection (≥ 80%) at the standard level of significance (P = 0.05).

Merf to write. Plant DM at harvest compared to a control treatment has been adopted in many studies of herbicidal effects, especially when studying products acceptable to organic growers (e.g. xxxxx). However, although in many instances a reduction in weed growth could be hoped for, total eradication of weeds by non-physical methods permissible in organic practice is unlikely. Dry matter may not be the best measure, as even a dead plant could contribute DM, and therefore blah bla d de blah hippy stuff.

Another problem of using 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, the only conclusion that could be made when species did not appear in the controls but did appear in oil treatments was that there was a positive association between plants biomass and oil application.

Conclusions

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

oilseed rape, proved effective. The usual caveats regarding organic herbicide action listed by Lanini (2010) such as cost, repeated applications, and thorough coverage, will probably also apply to the use of culinary oils a field setting. 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 the oils non-phytotoxic (Gan-Mor et al. 2012), so this route would not be open for oils intended for herbicide use. Overall, our study demonstrates that the application of culinary oils to weeds can reduce weed biomass in a manner acceptable to organic growers, and thus has the potential to be incorporated into a 'many hammers' approach to weed management in organic production systems.

Acknowledgements

The authors wish to thank to Brent Richards and Leona Meachen for help with plant maintenance.

References

AMRI I, HAMROUNI L, HANANA M, JAMOUSSI B (2013) Reviews on phytotoxic effects of essential oils and their individual components: news approach for weed management. *International Journal of Applied Biology and Pharmaceutical Technology* **4**, 96–114.

ASCARD J (1995) Effects of flame weeding on weed species at different developmental stages. *Weed Research* **35**, 397–411.

BOND W & GRUNDY AC (2001) Non-chemical weed management in organic farming systems. *Weed Research* **41**, 383–405.

DAYAN FE, CANTRELL CL, DUKE SO (2009) Natural products in crop protection. *Bioorg Med Chem* **17**, 4022–4034

DAYAN FE, OWENS DK, DUKE SO (2012) Rationale for a natural products approach to herbicide discovery. *Pest Management Science* **68**, 519–528

DUKE SO (2011) Why have no new herbicide mode of actions appeared in recent years? *Pest Management Science* 68, 505–512

GAN-MOR S, HETZRONI A, ELAD Y, RONEN B, MIZRACH A (2012) Technical note: compact energy-saving emulsifier for on-site production of edible oil-based control agents. *Transactions of the ASABE* **55**, 2079–2085.

GAUVRITZ C & CABANNE F (1993) Oils for weed control: uses and mode of action. *Pesticide Science* **37**, 147–153

HEINI J, MAINX H-G, GERHARDS R (2012) Evaluation of the potency of different seed oil ethoxylates to increase herbicide efficacy in comparison to commercial adjuvants. 25th German Conference on Weed Biology and Weed Control, March 13-15, 2012, Braunschweig, Germany. *Julius-Kuhn-Archiv*, **434**, 549–556.

IZADI-DARBANDI E, ALIVERDI A, HAMMAMI H (2013) Behavior of vegetable oils in relation to their influence on herbicides' effectiveness. *Industrial Crops and Products* **44**, 712–717

ISMAN MB (2000) Plant essential oils for pest and disease management. *Crop Protection* **19**, 603–608

ISMAN MB, MIRESMAILLI S, MACHIAL C (2011) Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products. Phytochem Review **10**, 197–204

LANINI WT (2010) Organic herbicides – do they work? *California Weed Science Society Journal* **6**, 1–3

LIEBMAN M, DAVIS AS (2009) Managing weeds in organic systems: an ecological approach. In: Charles Francis (Ed) *Organic Farming: The Ecological System*. Agronomy Monograph 54. pp 173–195

McERLICH AF, BOYDSTON RA. (2013) Current state of weed management in organic and conventional cropping systems. In: S.L. Young and F.J. Pierce (Eds) *Automation: The Future of Weed Control in Cropping Systems*. Springer, Dordrecht. pp 11–32.

ONOFRI A, CARBONELL EA, PIEPHO H-P, MORTIMER AM & COUSENS RD (2010) Current statistical issues in Weed Research. *Weed Research* **50**, 5–24

O'SULLIVAN J, VAN ACKER R, GROHS R & RIDDLE R (2015) Improved herbicide efficacy for organically grown vegetables. Org. Agr **5**, 315–322

PANNACCI E, KOPP MATHIASSEN S, KUDSK P (2010) Effect of adjuvants on the rainfastness and performance of tribenuron-methyl on broad-leaved weeds. *Weed Biology and Management* **10**, 126–131

PIEPHO H-P, WILLIAMS ER & FLECK M (2006) A note on the analysis of designed experiments with complex treatment structure. *HortScience* **41**, 446–452.

RAMEZANI S, SAHARKHIZ MJ, RAMEZANI F, FOTOKIAN MH (2008) Use of essential oils as bioherbicides. *Journal of Essential Oil Bearing Plants* **11**, 319–327,

RASMUSSEN J (2003) Punch planting, flame weeding and stale seedbed for weed control in row crops. *Weed Research* **43**, 393–403.

SAVILLE DJ (2015) Multiple comparison procedures - cutting the Gordian Knot. *Agronomy Journal* **107**, 730–735.

SYNOWIEC A, KALEMBA D, DROZDEK E, BOCIANOWSKI J (2017) Phytotoxic potential of essential oils from temperate climate plants against the germination of selected weeds and crops. Journal of Pest Science **90**, 407–419

TURK MA & TAWAHA AM (2003) Allelopathic effect of black mustard (*Brassica nigra* L.) on germination and growth of wild oat (*Avena fatua* L.). *Crop Protection* **22**, 673–677

YOUNG SL (2004) Natural product herbicides for control of natural vegetation along roadsides. *Weed Technology* **18**, 580–587

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

388

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	Oilseed rape	Processed
The Good Oil Extra Virgin Rapeseed Oil	Oilseed rape	Organic/raw
Amazing Haste Boiled Linseed Oil	Flax	Processed
Waihi Bush Organic Flax Seed Oil	Flax	Organic/raw

389

390

Table 2. Response of plants to foliar application of oilseed rape 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. [GH – glasshouse 22^{O}C; CR – cold room 15^{o}C]. P-values were obtained from nested ANOVA (see Methods for details) and means not sharing a letter code were separated as significantly different by Fisher's LSD ($P < 0.05$).

			Number of oil applications					
	Species	N	0	1	2	3	P_{Oil}	P_{Dose}
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)		310 ± 24 ^{a}	155 ± 35 ^{b}	156 ± 20 ^{b}	175 ± 22 ^{b}	< 0.001	0.776
GH	Natural weeds: species		3.15 ± 0.24 ^{a}	2.25 ± 0.37 ^{b}	2.50 ± 0.27 ^{b}	2.56 ± 0.29 ^{b}	< 0.001	0.821

Figure 1. Response of plants to foliar application of different culinary vegetable oils: flax, olive, sunflower and oilseed rape. light grey bars – processed oils; dark grey bars – raw/organic oils. Clover and poppy trials were run in a glasshouse with temperature 15-25^{O}C. Remaining plant trials were run in covered outdoor facility with temperature 10-20^{O}C. Values presented are mean (± se) relative dry weight (%) compared to control treatment. * indicates separation from control treatment by Fisher's unprotected LSD ($P < 0.05$).

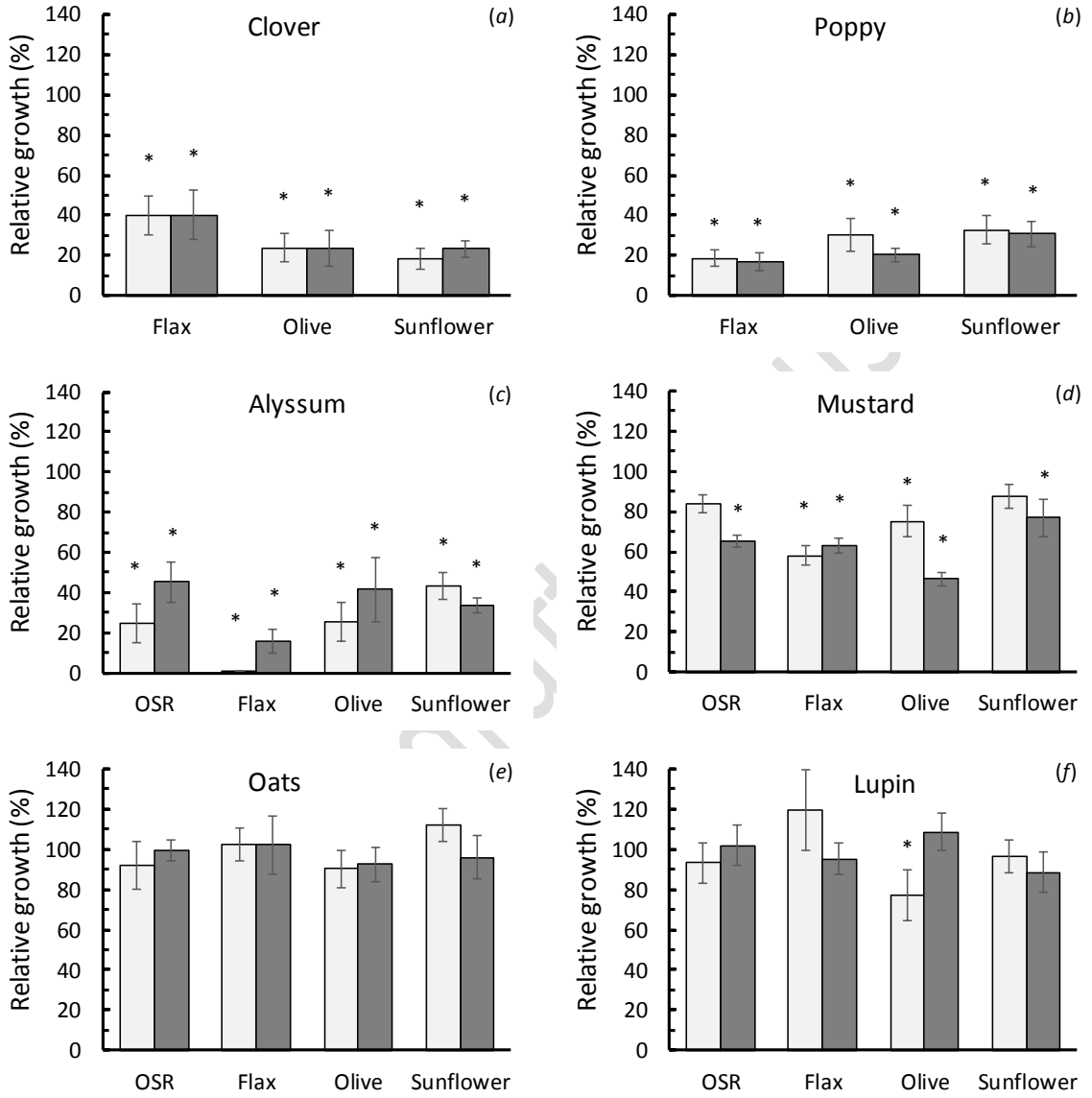
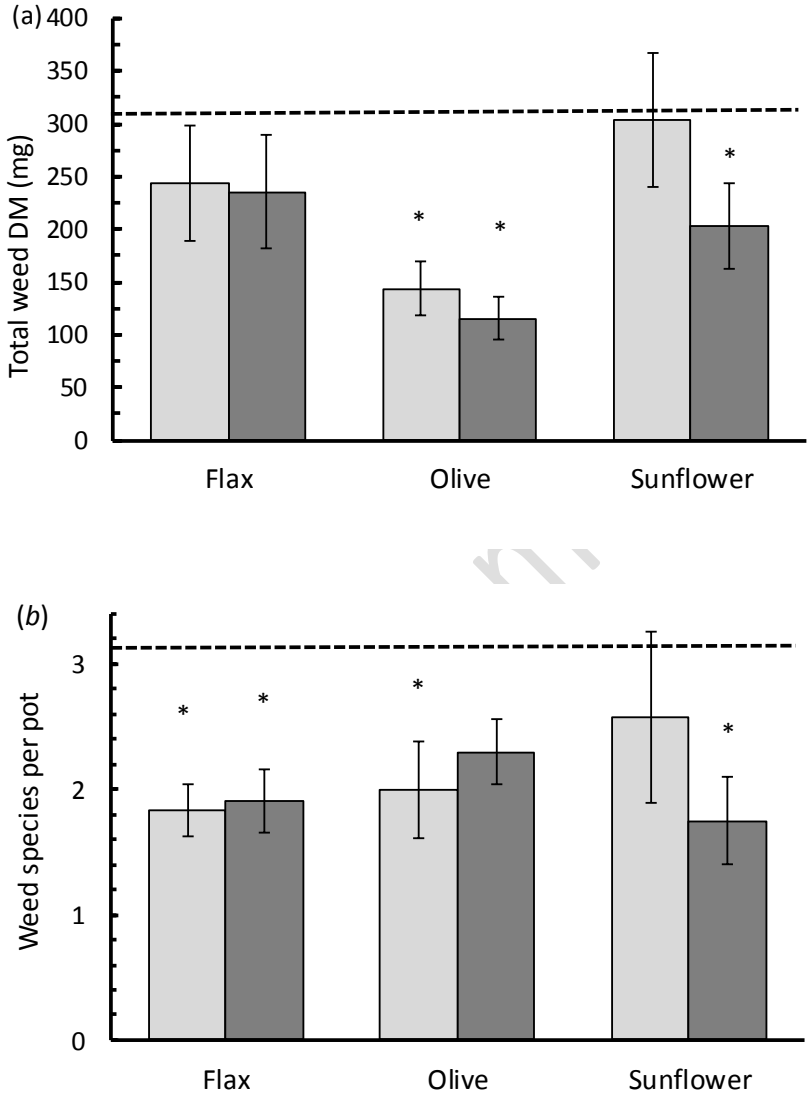


Figure 2. Response of naturally-emerging weeds to foliar application of different culinary vegetable oils (light grey – processed oils; dark grey – raw/organic oils). Values presented are mean per pot (± se) of (*a*) number of weed species and (*b*) total dry weight (mg) at final harvest. Dotted horizontal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



Appendices

Appendix 1

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

		Number of oil applications			
Family	**Species**	**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
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

Mean dry weight (mg) of weed species occurring in naturally-obtained soils at end of trial after spraying seedlings with various culinary oils.

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	309.50	243.70	235.10	303.40	203.70	143.50	115.10
Species	3.15	1.83	1.91	2.57	1.75	2.00	2.30