



Natural enemy enhancement and botanical insecticide source: a review of dual use companion plants

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Abstract

Intensive agriculture, which is associated with heavy inputs of synthetic insecticides, has serious ecological impacts, leading to loss of vital ecosystem services including insect-mediated pest suppression. In recent years, efforts have been made towards obtaining safer options to chemical insecticides for sustainable pest management. Habitat manipulation is a part of conservation biological control which aims at providing floral resources, alternative prey and shelter to predators and parasitoids to enhance and sustain natural pest suppression. The use of plant extracts as botanical insecticides is also an important provisioning ecosystem service. Selection of plant species for habitat manipulation has focused mainly on plants with suitable floral qualities to support natural enemies. To increase the benefits, habitat manipulation plants that can provide multiple ecosystem services in addition to floral resources would be an ideal. In this review, we focus on the potential of achieving the dual ecosystem services of bioinsecticidal source plants in addition to the provision of floral resources from selected plant species. Our literature search found 283 plants species from 44 plant families that have been involved in habitat manipulation studies. Fifteen of these plant families have species that have been exploited for their insecticidal properties. Three families, Apiaceae, Asteraceae and Lamiaceae, have the largest number of species that have been used for both habitat manipulation and botanical insecticides. Of the four most popular habitat manipulation plants, alyssum *Lobularia maritima* (L.) Desv. (Brassicaceae), buck wheat *Fagopyrum esculentum* Moench (Polygonaceae), coriander *Coriandrum sativum* L. (Apiaceae) and phacelia *Phacelia tanacetifolia* Benth. (Boraginaceae), buckwheat and coriander have been used for insecticidal purposes whilst no records exist of phacelia and alyssum as botanical insecticide species. There is great potential for identifying plant species that can support natural enemies as well as providing potent plant extracts as botanical insecticides by selecting species from the Apiaceae, Asteraceae and Lamiaceae families.

Keywords Habitat manipulation · Conservation biological control · Biopesticides · Dual ecosystem services

Introduction

Agriculture globally is facing many challenges including climate change, biodiversity loss and rising demands for food production (Deutsch et al. 2018; Rockstrom et al. 2009; Tilman et al. 2011). In response to these challenges, a growing volume of research is contributing towards a redesign of agricultural systems that provide nutritious food for all healthy and resilient ecosystems (Bommarco et al. 2013; Pretty et al. 2018; Struik and Kuyper 2017; Tilman et al. 2011). Evidence is growing that a sustainable intensification of agriculture can be achieved by combining scientific and farmer knowledge to develop ecologically and agronomically compatible practices (Pretty et al. 2018). Integrated pest management (IPM) is an example of redesigning intensive agricultural systems. Instead of

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relying principally on synthetic pesticides, IPM uses non-chemical or botanical insecticide measures to suppress pest population increase and a range of curative management tactics with synthetic pesticide use as last resort (Barzman et al. 2015). The declining availability of many pesticides due to resistance and deregistration, reflecting increasing awareness of their environmental and human health consequences, has driven changes towards ecologically based practices (Barzman et al. 2015; Borel 2017; Chagnon et al. 2015; Li et al. 2017; Sumon et al. 2018).

A central part of IPM is biological control in which natural enemies including parasitoids, predators and pathogens are introduced and/or promoted (Bale et al. 2008; Gurr et al. 2000a, 2018). Conservation biological control focuses on natural enemies already present in an agroecosystem and aims to maximize their impact on target pests by, for example, reducing the adverse effects of insecticide use (Begg et al. 2017; Ehler 1998). Habitat manipulation works in conjunction with conservation biological control and is used to provide conditions that promote natural enemies and suppress pest populations (Fiedler et al. 2008; Gurr et al. 2000b, 2017). This can include field level interventions such as establishing plants to provide floral resources, refuges and alternate hosts for natural enemies (Griffiths et al. 2008; Gurr et al. 2017). Plants that are selected for habitat manipulation have usually been studied for morphological and physiological floral characteristics that provide optimum benefits to natural enemies (Baggen et al. 1999; Balzan et al. 2014). Habitat manipulation tactics can extend beyond the field to include landscape features including riparian areas and treelines, although the effect of landscape features on crop pests is variable (Karp et al. 2018; Tschardt et al. 2007).

Ecologically based pest management tactics such as conservation biological control have been shown to reduce the use of synthetic insecticides in a variety of cropping systems whilst maintaining or increasing crop yields and efforts are being made to up scale the practice globally (Pretty et al. 2018; Wyckhuys et al. 2013; Xu et al. 2017). Despite these advantages, however, uptake of conservation biological control on a wide scale is limited (Gurr et al. 2016). In cases where uptake has been strong, the vegetation used in habitat manipulation provides multiple ecosystem services rather than suppressing pests alone (Khan et al. 2006, 2012). To date, however, there is a major gap in knowledge about the possibility of habitat manipulation plants providing botanical insecticides. This is important because synthetic insecticides present significant risks to human health. Agricultural workers and consumers are at risk of being negatively affected by insecticide products, tank mixes, drift, residues and breakdown products, especially as a consequence of poor registration, storage and misuse (Eddleston et al. 2002). In agricultural areas where there are high illiteracy rates, and

poor training and equipment, the impacts are especially high (Amoabeng et al. 2017; Williamson et al. 2008).

Many plants possess secondary metabolites such as alkaloids, phenols and terpenoids that can have insecticidal activity such as toxicity, repellency, feeding deterrence against insect pests (Koul 2004). Botanical insecticides, including extracts and essential oils of these plant species, have been used to protect crops against insect herbivory for many years (Belmain et al. 2012; Isman 2000, 2008). Synthetic insecticides often have lethal and sub-lethal effects on natural enemies (Desneux et al. 2007). Biopesticides are considered relatively benign to non-target species owing to their rapid breakdown, selectivity nature and reduced risk of insecticide resistance as plant extract, particularly crude extracts have multiple modes of action other than toxicity, such as repellency (Amoabeng et al. 2013; Dubey et al. 2011; Isman 2006; Koul et al. 2008; Tembo et al. 2018). Another important benefit of botanicals is that they tend to depend on “suites” of closely related active constituents rather than a single active ingredient; this diversity may delay or mitigate the development of resistance in pest populations to most botanicals (Koul 2004). Biopesticides have been used for centuries as means of managing pests until synthetic insecticides replaced plant extracts (Isman 1997). The interest in botanical insecticides is increasing but still accounts for less than 1% of crop protectants used globally (Isman 2008, 2017). In developing countries, plant extracts are often prepared from common weed species that grow around the field and obtained freely, with labour as the only cost, resulting in cheaper pest management option when compared with synthetic insecticides (Amoabeng et al. 2014; Isman 2017).

The field of botanical pesticides is highly active [see reviews by Boulogne et al. (2012), Isman and Grieneisen (2014), Isman (2017), Yang and Tang (1988)] but this review considers two novel aspects. First, we assess the extent to which the plant species used in conservation biological control studies have been the subject of research to determine if they have potentially useful biopesticidal properties. Second, we consider the practicalities of using plants that have dual use in promoting biological control and as sources of botanical pesticides (Fig. 1).

Conservation biological control plant species

The identification of plant species studied for habitat manipulation purposes began with the published review by Fiedler et al. (2008) and was followed by a search on the online ISI Web of Science database to from 1989 to 2018 using search terms: *flower** AND “conservation biological control”, *flower** AND “natural enemy”, and “habitat management”

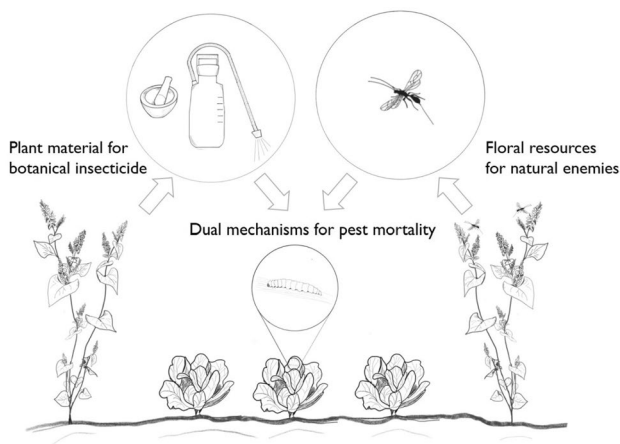


Fig. 1 A secondary plant species (such as buckwheat in this example) can potentially provide dual benefits for pest management, promoting biological control and providing insecticidal compounds to treat the crop

AND “conservation biological control”. Between 1989 and 2006, 165 plant species belonging to 35 plant families were used in habitat manipulation studies. The criteria that were applied to the Fiedler et al. (2008) plant species included their effectiveness in previous habitat manipulation studies, frequency of natural enemy visitation, long flowering duration, availability of seeds, ease of establishment, agronomic suitability and the value of the plant as cover or alternative crop (Fiedler et al. 2008). The same search criteria were applied to conduct a follow-up database search (Table 1). Each plant species is listed once irrespective of the number of studies in which it was used. Where a plant was involved in more than one study, only one example reference is given.

Habitat manipulation studies from 1989 to 2006 involved 165 plant species belonging to 35 families and 188 new species from 29 families were the subject of work published between 2007 and 2018. The number of publications per year between 2007 and 2018 ranges from three (2009 and 2010) to ten in the first half of 2018 (Fig. 2). Conservation biological control studies are dominated by research from developed countries in North America and Europe as well as Australia, New Zealand and Japan (Wyckhuys et al. 2013). Tropical regions have more flowering species than temperate areas so there remains great potential of identifying additional plant species for use in habitat manipulation (Christenhusz and Byng 2016).

Plant families used in habitat manipulation with insecticidal activity

A search in Google, Google Scholar and Scopus using both the scientific and common names of each of the 283 plant species named in papers on conservation for the

terms “botanical insecticide”, “plant extracts”, biopesticides, “insecticidal activity” OR “pesticidal activity” revealed 15 (33.3%) (Apiaceae, Apocynaceae, Asteraceae, Boraginaceae, Brassicaceae, Campanulaceae, Fabaceae, Lamiaceae, Myrtaceae, Papaveraceae, Polygonaceae, Primulaceae, Proteaceae, Rosaceae, Rubiaceae and Scrophulariaceae) out of 44 plant families that have been involved in habitat manipulation studies, had at least one plant genus or species with insecticidal activity. Proteaceae had one plant used in habitat manipulation in the same genus as another plant used as a biopesticide. All other plant families had at least one plant species tried for its insecticidal activity and tested in habitat manipulation studies.

Three families, Apiaceae, Asteraceae and Lamiaceae, had more than ten species with insecticidal activity and accounted for more than 70% of plant species studied. These families also had the highest number of species used in habitat manipulation studies. Of the 18 plant species in Apiaceae involved in habitat manipulation studies, 13 (72.2%) have been tested and showed insecticidal activity. In the Asteraceae, 19 (25.7%) out of the 74 plant species involved in habitat manipulation studies have been tested for their insecticidal activity. In addition, five more plants species in the same genus as some of the species for habitat manipulation studies have been used for their insecticidal activity. Lamiaceae had 11 (39.3%) out of the 28 plants involved in habitat manipulation studies having insecticidal activity. Two families, Brassicaceae and Fabaceae, had several species involved in habitat manipulation studies but not many species in the families have been known to have insecticidal properties. Among the 14 species in the Brassicaceae family, five were identified to have activity against insects whilst two out of the 23 species in Fabaceae were identified to have activity against insects. *Fagopyrum esculentum* is one of the most studied species in habitat manipulation programs (Fiedler et al. 2008; Lavandero et al. 2006; Vattala et al. 2006) and was the only species with insecticidal activity among 12 species in Polygonaceae. At 2,500 ppm, a methanol extract of the grains of buckwheat was potent against the green peach aphid *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) (Lee and Rasmussen 2000).

Boulogne et al. (2012) reviewed plant families and species with insecticidal activity and found that 656 plant species belonging to 110 families are known to have insecticidal activity in which Lamiaceae alone had 181 (28%) followed by Fabaceae, Asteraceae and Apiaceae. In all, 30 (66.8%) out of the 44 plant families in this review do not have insecticidal activity. It is, however, possible that plant species in these families have not yet been studied enough for their activity against insects.

Table 1 “Gap identification” of plants researched for conservation biological control and that have yet to be the subject of work to identify scope as sources of botanical insecticides (denoted by ‘o’) and plants that constitute “proof of concept” in having insecticidal proper-

ties as well as utility in conservation biological control (denoted by ‘+’; or more tentatively by a ‘x’ denoting a plant in the same genus showed insecticidal activity)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
Apiaceae					
<i>Ammi majus</i> L.	Bishop’s flower	+	Lepidoptera	1	*
<i>Ammi visnaga</i> (L.) Lamarck	Toothpick ammi	+	Diptera	2, 3	*
<i>Anethum graveolens</i> L.	Dill	+	Coleoptera, Blattodea, Diptera, Lepidoptera	4, 5, 6	*
<i>Angelica atropurpurea</i> L.	Angelica	o			*
<i>Anthriscus cerefolium</i> (L.)	Chervil	+	Coleoptera, Diptera	7	*
<i>Anthriscus sylvestris</i> (L.) Hoffmann	Cow parsley	+	Lepidoptera, Diptera	63	*
<i>Apium graveolens</i> L.	Celery	+	Diptera	8	*
<i>Carum carvi</i> L.	Caraway	+	Coleoptera	9	*
<i>Conium maculatum</i>	Poison hemlock	+	Thysanoptera, Trombidiformes, Hemiptera	10, 11	10
<i>Conopodium majus</i>	Pignut	o			13
<i>Coriandrum sativum</i> L.	Coriander/cilantro	+	Coleoptera	12, 13	13
<i>Daucus carota</i> L.	Wild carrot	+	Diptera, Coleoptera	14, 15	*
<i>Foeniculum vulgare</i> Mill.	Fennel	+	Coleoptera	12, 16, 17	*
<i>Heracleum sphondylium</i> L.	Eltrot	o			*
<i>Heracleum maximum</i> Bartr.	Cow parsnip	x	Coleoptera	18	*
<i>Pastinaca sativa</i> L.	Wild parsnip	+	Lepidoptera	19	2
<i>Pimpinella anisum</i>	Aniseed	+	Diptera	20, 21	10
<i>Zizia aurea</i> (L.) Koch	Golden alexanders	o			*
Apocynaceae					
<i>Apocynum cannabinum</i> L.	Indian hemp	o			*
<i>Asclepias syriaca</i>	Common milkweed	o			22
<i>Asclepias tuberosa</i>	Butterfly weed	o			22
<i>Asclepias fascicularis</i> Dcne.	Milkweed	o			*
<i>Asclepias incarnata</i> L.	Swamp milkweed	o			*
<i>Asclepias syriaca</i> L.	Common milkweed	o			*
<i>Asclepias tuberosa</i> L.	Butterfly weed	o			*
Asparagaceae					
<i>Asparagus acutifolius</i>	Wild asparagus	o			13
Asteraceae					
<i>Achillea millefolium</i> L.	Yarrow	+	Lepidoptera, Coleoptera	22, 24	*
<i>Achillea</i> spp.	Yarrow	+	Lepidoptera, Coleoptera	23, 24	*
<i>Ageratina aromatic</i>	Lesser snakeroot	x	Diptera	25	14
<i>Andryala integrifolia</i>	Common andryala	o			11
<i>Anthemis arvensis</i> L.	Corn chamomile	x	Lepidoptera	26	*
<i>Artemisia ludoviciana</i>	Louisiana wormwood	+	Hemiptera, Orthoptera	27, 28	16
<i>Aster nova-angliae</i> L.	Smooth aster	x	Lepidoptera	26	*
<i>Aster novi-belgii</i> L.	New England aster	+	Lepidoptera	26	*
<i>Baccharis pilularis</i> DC.	New York aster	o			*
<i>Baccharis viminea</i> DC.	Coyotebrush	o			*
<i>Cacalia atriplicifolia</i> L. H. Rob.	Mule fat	o			*
<i>Calendula arvensis</i>	Field marigold	x	Lepidoptera	29	7
<i>Calendula officinalis</i> L.	Calendula	+	Hemiptera	30	*

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Centaurea cyanus</i> L.	Garden cornflower	+	Hemiptera	30	*
<i>Centaurea jacea</i> L.	Brownray knapweed	+	Hemiptera	30	*
<i>Centaurea montana</i> L.	Mountain bluet	x	Hemiptera	30	*
<i>Chondrilla juncea</i>	Devil's grass	+	Coleoptera	64	13
<i>Chrysanthemum maximum</i> x <i>superbum</i> cv. Snow Lady	Max chrysanthemum	o			*
<i>Chrysanthemum segetum</i> (L.) Fourr.	Corn marigold	o			*
<i>Cichorium intybus</i> L.	Chickory	+	Diptera	31	*
<i>Conoclinium coelestinum</i>	Blue mistflower	o			14
<i>Coreopsis lanceolata</i> L.	Sand coreopsis	o			*
<i>Coreopsis tinctoria</i> Nutt.	Golden tickseed	o			*
<i>Coreopsis verticillata</i> L.b	Coreopsis	o			*
<i>Cosmos bipinnatus</i>	Garden cosmos	–	Diptera (less efficacious)	a	9
<i>Cosmos sulphureus</i>	Yellow cosmos	o			18
<i>Crepis biennis</i>	Rough hawksbeard	o			12
<i>Crepis capillaris</i>	Smooth hawksbeard	o			11
<i>Dittrichia viscosa</i>	False yellowhead	+	Hemiptera	32	13
<i>Echinacea pallida</i>	Pale purple coneflower	–	Lepidoptera	b	16
<i>Echinacea purpurea</i> (L.) Moench	Purple coneflower	+	Lepidoptera	23	*
<i>Erigeron speciosus</i>	Garden fleabane	o			1
<i>Eupatorium hyssopifolium</i>	Hyssopleaf thoroughwort	+	Hemiptera, Diptera	33	22
<i>Eupatorium perfoliatum</i> L.	Boneset	o			*
<i>Gaillardia aristata</i> Pursh	Common gaillardia	o			*
<i>Gaillardia pulchella</i> Foug.	Firewheel	o			*
<i>Gazania rigens</i> (L.) Gaertn.	Treasure-flower	o			*
<i>Helianthus annuus</i> L.	Sunflower	+	Isoptera, Coleoptera	34, 35	*
<i>Helianthus petiolaris</i>	Lesser sunflower	o			1
<i>Helianthus strumosus</i> L.	Pale-leaved sunflower	o			*
<i>Helichrysum bracteatum</i> (Vent.) Andr.	Bracted strawflower	+		65	*
<i>Heliopsis helianthoides</i>	False sunflower	o			16
<i>Heterotheca grandiflora</i>	Telegraphweed	o			1
<i>Hypochaeris radicata</i>	Catsear, flatweed	o			12
<i>Layia platyglossa</i> (Fisch. & C.A. Mey.) Gray	Tidy tips	o			*
<i>Leontodon hispidus</i>	Rough hawkbit	o			12
<i>Leucanthemum vulgare</i> Lam.	Oxeye daisy	o			*
<i>Leucanthemum x superbum</i>	Shasta daisy	o			*
<i>Liatris aspera</i> Michx.	Rough blazing star	o			*
<i>Matricaria chamomilla</i>	Scented mayweed	+	Coleoptera	36	17
<i>Matricaria recutita</i>	Camomile	o			9
<i>Melampodium paludosum</i> L.	Medallion flower	o			*
<i>Oligoneuron rigidum</i>		o			16
<i>Pityopsis graminifolia</i>	Narrowleafsilgrass	o			14
<i>Ratibidacolumnifera</i> (Nutt.) Woot. & Standl.	Prairie coneflower	o			*
<i>Ratibida pinnata</i> (Vent.) Barnh.	Yellow coneflower	o			*
<i>Rudbeckia hirta</i> L.	Blackeyed Susan	+		66	*

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Senecio obovatus</i> Muhl. ex Willd.	Round-leaved ragwort	o			*
<i>Senecio vulgaris</i>	Old-man-in-the-Spring	–	Coleoptera	c	7
<i>Silphium perfoliatum</i> L.	Cup plant	–	Diptera	d	*
<i>Silybum marianum</i>	Saint Mary's thistle	o			17
<i>Solidago canadensis</i> L.	Late goldenrod	+	Diptera	67	*
<i>Solidago juncea</i>	Early goldenrod	o			20
<i>Solidago riddellii</i> Frank ex Riddell	Riddell's goldenrod	o			*
<i>Solidago speciosa</i> Nutt.	Showy goldenrod	o			*
<i>Solidago</i> spp	Goldenrod	o			*
<i>Symphotrichum shortii</i>	Short's aster	o			16
<i>Tagetes erecta</i>	Aztec marigold	+	Coleoptera	15	4
<i>Tagetes panda</i>		o			2
<i>Tagetes patula</i> L.	French marigold	+	Diptera	37	*
<i>Tanacetum vulgare</i> L.	Common tansy	+	Lepidoptera	68	*
<i>Vernonia missurica</i> Raf.	Ironweed	o			*
<i>Zinnia elegans</i> Jacquin	Common zinnia	–	Hemiptera	e	*
<i>Zinnia hybrida</i>		o			18
Boraginaceae					
<i>Borago officinalis</i> L.	Borage	+	Coleoptera	38	*
<i>Echium lycopsis</i> L. p.p.	Borage	x			*
<i>Echium plantagineum</i>	Purple viper's-bugloss	o			13
<i>Echium vulgare</i> L.	Common viper's bugloss	+	Lepidoptera	39	*
Brassicaceae					
<i>Aurinia saxitalis</i> (L.) Desv.	Aurinia	o			*
<i>Brassica juncea</i> (L.) Czern.	Mustard	+	Coleoptera	69	*
<i>Camelina sativa</i>	Gold-of-pleasure	o			8
<i>Capsella bursa-pastoris</i>	Shepherd's purse	o			13
<i>Diplotaxis tenuifolia</i>	Perennial wall-rocket	o			17
<i>Hirschfeldia incana</i>	Shortpod mustard	o			17
<i>Iberis</i> sp.	Candytuft	o			*
<i>Lobularia maritima</i> (L.) Desv.	Alyssum	o			*
<i>Moricandia</i> sp	Violet cabbage	o			19
<i>Nasturtium</i> sp.		o			*
<i>Raphanus sativus</i> L.	Daikon/radish	+	Diptera	40	*
<i>Raphanus raphanistrum</i>	White charlock	+	Coleoptera	41	13
<i>Sinapis alba</i> L.	White mustard	+	Diptera, Lepidoptera	40, 42	*
<i>Sinapis arvensis</i>	Wild mustard	+	Lepidoptera	42	8
Campanulaceae					
<i>Campanula glomerata</i> L.	Bell flower	o			*
<i>Campanula persicifolia</i> L.	Peach-leaved bellflower	o			*
<i>Campanula rotundifolia</i>	Harebell	–	Lepidoptera	f	1
<i>Jasione montana</i>	Sheep's bit scabious	o			11
<i>Lobelia cardinalis</i> L.	Cardinal flower	o			*
<i>Lobelia siphilitica</i> L.	Great blue lobelia	+	Diptera	43	*
Caprifoliaceae					
<i>Knautia arvensis</i>	Field scabious	o			12
<i>Lonicera etrusca</i>	Etruscan honeysuckle	o			7

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Sambucus mexicana</i> K. Presl ex DC.	Elderberry	o			*
<i>Sambucus racemosa</i> L.	Red-berried elder	o			*
Caryophyllaceae					
<i>Agrostemma githago</i>	Common corncockle	o			*
<i>Gypsophila</i> sp.	Gypsophila	o			*
<i>Gypsophila elegans</i>	Showy baby's-breath	o			9
<i>Silene alba</i> (P. Mill.) Krause	Bladder campion	–	Hemiptera	e	*
<i>Silene gallica</i>	Common catchfly	o			13
<i>Spergula arvensis</i>	Corn spurry	o			13
<i>Stellaria media</i>	Chickweed	o			7
Chenopodiaceae					
<i>Chenopodium quinoa</i> Willd.	Quinoa	o			*
Euphorbiaceae					
<i>Euphorbia epithymoides</i> L.	Flowering spurge	o			*
Fabaceae					
<i>Amorphanthes Pursh</i>	Leadplant	x	Diptera	44	*
<i>Cassia fasciculata</i> Michx.	Partridge pea	o			*
<i>Crotalaria juncea</i>	Sun hemp	+	Coleoptera	45	6
<i>Dalea purpurea</i>	Purple prairie clover	o			16
<i>Desmodium canadense</i> (L.) DC.	Showy tick trefoil	o			*
<i>Lespedeza hirta</i> (L.) Hornem.	Hairy bush-clover	o			*
<i>Lotus corniculatus</i> L.	Bird's foot trefoil	o			*
<i>Lupinus albus</i> L.	White lupine	o			*
<i>Medicago lupulina</i>	Black medick	o			12
<i>Medicago sativa</i> L.	Alfalfa	o			*
<i>Lotus australis</i>	Austral trefoil	o	–		3
<i>Onobrychis viciifolia</i>	Common sainfoin	o			1
<i>Ononis natrix</i>	Shrubby rest-harrow	o			2
<i>Phaseolus vulgaris</i>	Common bean	o			15
<i>Trifolium hybridum</i>	Alsike clover	o			2
<i>Trifolium incarnatum</i> L.	Crimson clover	o			*
<i>Trifolium pratense</i>	Red clover	o			2
<i>Trifolium repens</i> L.	Ladino, white clover	o			*
<i>Trifolium subterraneum</i> L.	Subclover	o			*
<i>Vicia cracca</i>	Tufted vetch	o			2
<i>Vicia faba</i> L.	Faba bean	+	Hemiptera	46	*
<i>Vicia sativa</i> L.	Common vetch	o			*
<i>Vicia villosa</i>	Hairy vetch	o			10
Gentianaceae					
<i>Exacum</i> sp.	Exacum	o			*
<i>Geranium endressii</i> Gayd	Cranesbill	o			*
<i>Geranium maculatum</i> L.	Wild geranium	o			*
<i>Geranium pyrenaicum</i>	Hedgerow cranesbill	o			12
Hydrophyllaceae					
<i>Hydrophyllum virginianum</i> L.	Virginia waterleaf	o			*
<i>Nemophilamenziesii</i> Hook. & Arn.	Baby blue eyes	o			*
<i>Phacelia campanularia</i> Gray	Wild Canterbury bells	o			*

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Phacelia tanacetifolia</i> Benth.	Phacelia	o			*
Hypericaceae					
<i>Hypericum perforatum</i>	Common Saint John's wort	o			13
Iridaceae					
<i>Iris germinica</i> L.	Iris	o			*
Lamiaceae					
<i>Acinos arvensis</i> Dandy	Basil thyme	o			*
<i>Agastache foeniculum</i> (Pursh)	Anise hyssop	+	Diptera	2	*
<i>Agastache nepetoides</i> (L.) Kuntze	Yellow giant hyssop	o			*
<i>Agastache rugose</i> Fisch. & C.A.Mey.)	Korean licorice mint	–	Coleoptera	g	*
<i>Buddleja davidii</i>	Orange eye	o			14
<i>Calamintha baetica</i> Mill.	Woodland calamint	o			13
<i>Calamintha nepeta</i>	Lesser calamint	+	Diptera	47	14
<i>Clinopodium vulgare</i>	Wild basil	o			2
<i>Cordia verbanacea</i> (Jacq.)	Cordia	–	Coleoptera	h	5
<i>Lamium purpureum</i> L.	Red dead-nettle	o			7
<i>Lavandula stoechas</i> L.	French lavender	+	Diptera, Coleoptera	2, 48	13
<i>Mellisa officinalis</i> L.	Common balm	+	Lepidoptera	49	5
<i>Mentha piperita</i> L.	Peppermint	+	Coleoptera, Diptera	50	5
<i>Mentha satuireioides</i> R.Br.	Bushmint	+	Lepidoptera, Hemiptera	51	3
<i>Mentha spicata</i> L.	Spearmint	+	Diptera	52	*
<i>Monarda citriodora</i> Cerv. ex Lag.	Lemon bee balm	o			*
<i>Monarda fistulosa</i> L.	Bee balm	+	Trombidiformes	53	20
<i>Monarda punctata</i> L.	Horsemint	o			*
<i>Ocimum basilicum</i> L.	Basil	+	Coleoptera, Lepidoptera, Hemiptera	17, 54	5
<i>Origanum vulgare</i> L.	Wild marjoram	+	Trombidiformes, Lepidoptera	53, 62	12
<i>Prunella vulgaris</i> L.	Selfheal	o			*
<i>Pycnanthemum tenuifolium</i> Schrad.	Common horsemint	o			22
<i>Rosmarinus officinalis</i> L.	Rosemary	+	Coleoptera	12, 55	7
<i>Salvia farinacea</i> Benth.	Mealy-cup sage	o			*
<i>Salvia uliginosa</i> Benth.	Bog sage	o			*
<i>Salvia viridis</i> L.	Clary sage	o			*
<i>Scutellaria integrifolia</i> L.	Helmet flower	o			22
<i>Westringia fruticose</i> (Willd.) Druce	Coastal rosemary	o			3
Liliaceae					
<i>Allium cernuum</i> Roth	Nodding wild onion	o			*
<i>Convallaria majalis</i> L.	Lily of the valley	o			*
Linaceae					
<i>Linum grandiflorum</i> Desf.	Scarlet fla	o			*
Lythraceae					
<i>Lythrum salicaria</i> L.	Purple loosestrife	o			12
Malvaceae					
<i>Malva moschate</i> L.	Musk mallow	o			12
<i>Malva neglecta</i> Wallr.	Common mallow	o			13
<i>Malva sylvestris</i> L.	High mallow	o			7

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
Myrtaceae					
<i>Callistemon citrinus</i> (Curtis)	Crimson/common red	+	Coleoptera	56	3
<i>Leptospermum</i> cv Rudolpd	Tea tree	o			3
Onagraceae					
<i>Clarkia amoena</i> (Lehm.) A. Nels. & J.F. Macbr.	Farewell-to-spring	o			*
<i>Clarkia concinna</i> (Fisch. & C.A. Mey.) Greene	Red ribbons	o			*
<i>Clarkia unquiculata</i> Lindl.	Elegant clarkia	o			*
<i>Oenothera speciosa</i> Nutt.	Pinkladies	o			*
<i>Oenotherabiennis</i> L.	Evening primrose	o			*
Paeoniaceae					
<i>Paeonia lactiflora</i> Pallas	Peony	o			*
Papaveraceae					
<i>Eschscholzia californica</i> Cham.	California poppy-	o			*
<i>Papaver rhoeas</i> L.	Common poppy	o			*
<i>Papaver somniferum</i>	Opium poppy	+	Isoptera	57	17
<i>Stylomecon heterophylla</i> (Benth.) G. Taylor	Wind poppy	o			*
Plantaginaceae					
<i>Penstemon digitalis</i> Nutt. ex Sims	foxglove beard-tongue	o			1
<i>Veronicastrum virginicum</i>		o			16
<i>Veronica persica</i> Poir.	Common field-speedwell	o			7
Poaceae					
<i>Agrostis capillaries</i> L.	Colonial bent	o			2
<i>Andropogon gerardi</i> Vitman	Big bluestem	o			16
<i>Bouteloua curtipendula</i> (Michx.) Torr.	Side oats grama	o			16
<i>Cynosurus cristatus</i> L.	Crested dog's-tail	o			2
<i>Elymus Canadensis</i> L.	Canada wild rye	o			16
<i>Festuca rubra</i> L.	Red fescue	o			2
<i>Panicum virgatum</i> L.	Switchgrass	o			16
<i>Poa pratensis</i> L.	Kentucky bluegrass	o			2
<i>Schizachyrium coparium</i> (Michx.) Nash	Little bluestem	o			22
<i>Sorghastrum nutans</i> (L.) Nash	Yellow Indiangrass	o			16
<i>Sporobolus clandestinus</i> (Biehler) A.S. Hitchc.	Rough dropseed	o			16
Polemoniaceae					
<i>Gilia tri-color</i> Benth.	Bird's eyes	o			*
<i>Linanthus grandiflorus</i> (Benth.) Greene	Mountain phlox	o			*
Polygonaceae					
<i>Eriogonum compositum</i>	Arrowleaf buckwheat	o			14
<i>Eriogonum douglasii</i>	Douglas' buckwheat	o			14
<i>Eriogonum elatum</i> Dougl. ex Benth.	Tall woolly buckwheat	o			14
<i>Eriogonum fasciculatum</i> Benth.	California buckwheat	o			*
<i>Eriogonum giganteum</i> S. Wats.	St Catherine's lace	o			

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Eriogonum heracleoides</i>	Parsnipflower buckwheat	o			14
<i>Eriogonum microthecum</i>	Slender buckwheat	o			14
<i>Eriogonum niveum</i>	Snow buckwheat	o			14
<i>Eriogonum sphaerocephalum</i>	Rock buckwheat	o			14
<i>Eriogonum strictum</i>	Blue Mountain buckwheat	o			14
<i>Eriogonum thymoides</i>	Thymeleaf buckwheat	o			14
<i>Fagopyrum esculentum</i> Moench	Buckwheat	+	Hemiptera	58	*
Primulaceae					
<i>Primula veris</i> L.	Cowslip	+	Coleoptera	59	2
Proteaceae					
<i>Grevillea</i> cv Bronze Rambler		x			3
Ranunculaceae					
<i>Anemone canadensis</i> L.	Canada anemone	o			*
<i>Aquilegia canadensis</i> L.	Columbine	o			*
<i>Consolida ambigua</i> (L.) P.W. Ball & Heywood	Doubtful knight's-spur	o			*
<i>Ranunculus ollissiponensis</i> Pers		o			7
<i>Thalictrum aquilegifolium</i> L.	Meadow rue	o			*
Rhamnaceae					
<i>Ceanothus</i> sp.	California lilac	o			*
<i>Ceanothus americanus</i> L.	New Jersey tea	o			*
<i>Rhamnus californica</i> Eschsch.	Coffeeberry	o			*
Rosaceae					
<i>Fragaria virginiana</i> Duchesne	Wild strawberry	o			*
<i>Heteromeles arbutifolia</i>	Toyon	o			*
<i>Potentilla fruticosa</i> auct. non L.	Shrubby cinquefoil	o			*
<i>Prunus ilicifolia</i> Nutt. ex Hook. & Arn.	Hollyleaf cherry	o			*
<i>Quillaja saponaria</i> Molina	Soapbark tree	+	Diptera	60	*
<i>Rosa setigera</i> Michx.	Michigan rose	o			*
<i>Spiraea alba</i> Duroi	Meadowsweet	o			*
Rubiaceae					
<i>Cephalanthus occidentalis</i> L.	Buttonbush	o			*
<i>Galium aparine</i> L.	Cleavers	+	Lepidoptera	61	14
<i>Galium verum</i> L.	Yellow bedstraw	o			12
Rutaceae					
<i>Ruta graveolens</i> L.	Rue	–	Coleoptera	h	*
Salicaceae					
<i>Salix</i> sp.	Willow	o			*
Saxifragaceae					
<i>Astilbe x arendsii</i>	Bridal veil	o			*
<i>Heuchera americana</i> L.	Alum root	o			*
Scrophulariaceae					
<i>Collinsia heterophylla</i> Buist ex Graham	Chinese houses	o			*
<i>Linaria maroccana</i> Hook. f.	Toadflax	o			*
<i>Myoporum parvifolium</i> R.Br.	Creeping boobialla	o			3
<i>Linaria saxatilis</i> L.		+	Coleoptera	16	13
<i>Penstemon hirsutus</i> (L.) Willd.	Penstemon	o			*

Table 1 (continued)

Scientific name	Common name	Botanical insecticide activity	Order of insects controlled	Ref as botanical species	Ref as HM species
<i>Scrophularia marilandica</i> L.	Late figwort	o			*
<i>Verbascum phlomoides</i> L.	Orange mullein	o			*
Solanaceae					
<i>Nicotiana alata</i> × <i>sanderac</i> Link & Otto	Flowering tobacco	o			*
<i>Petunia</i> × <i>hybrida</i> Vilmg	Petunia	o			*
Tropaeolaceae					
<i>Tropaeolum majus</i> L.	Nasturtium	o			*
Urticaceae					
<i>Urtica urens</i> L.	Dwarf nettle	o			17
Verbenaceae					
<i>Aloysia virgate</i> Paláu	Beebrushes	o			14
<i>Phyla nodiflora</i> (L.) Greene	Frog fruit	o			14
<i>Verbena canadensis</i> (L.) Brittonh	Rose verbena	o			*
<i>Verbena stricta</i> Vent.	Hoary vervain	o			*

Data set based on the literature published from 1989 to 2018; species with * are from Fiedler et al. (2008) review of conservation biological control

Plants involved in habitat manipulation from 1989 to 2018. Species with * are from Fiedler et al. (2008)

Reference for habitat manipulation plant species with * are found in Fiedler et al. (2008)

+ Insecticidal activity

– Plant species tested against insects but with less/no activity

O plant species not tested

X Different species in the same genus with insecticidal activity

References for plants for habitat manipulation: 1. (Pellissier and Jabbour 2018) 2. (Campbell et al. 2017) 3. (Pandey et al. 2018) 4. (Haro et al. 2018) 5. (Batista et al. 2017) 6. (Trisnawati and Azis 2017) 7. (Villa et al. 2016) 8. (Tschumi et al. 2016) 9. (van Rijn et al. 2016) 10. (van Rijn et al. 2016) 11. (Villa et al. 2016) 12. (Hatt et al. 2017) 13. (Nave et al. 2016) 14. (Sivinski 2014) 15. (Balzan et al. 2014) 16. (Gill et al. 2014) 17. (Martinez-Una et al. 2013) 18. (Gontijo et al. 2013) 19. (Diaz et al. 2012) 20. (Walton and Isaacs 2011) 21. (Tuell et al. 2008) 22. (Frank et al. 2008)

Reference as botanical insecticide. 1. (El-Ghar et al. 1996) 2. (Ebadollahi 2013) 3. (Pavela et al. 2016) 4. (Babri et al. 2012) 5. (Sousa et al. 2013) 6. (Sousa et al. 2015) 7. (Evergetis and Haroutounian 2014) 8. (Khater and Khater 2009) 9. (Lopez et al. 2008) 10. (Chermenskaya et al. 2010) 11. (Gokce et al. 2016) 12. (Pavela and Benelli 2016) 13. (Rani 2012) 14. (Momin and Nair 2002) 15. (Azad et al. 2013) 16. (Koul et al. 2008) 17. (Cosimi et al. 2009) 18. (Alkan et al. 2017) 19. (Berenbaum et al. 1991) 20. (Santos et al. 1998) 21. (Park et al. 2006) 22. (Hasheminia et al. 2011) 23. (Pavela 2010) 24. (Nenaah et al. 2015) 25. (Rajeswary and Govindarajan 2013) 26. (Kumar et al. 2017) 27. (Rizvi et al. 2018) 28. (Blust and Hopkins 1987) 29. (Medhini et al. 2012) 30. (Alexenizer and Dorn 2007) 31. (Mansour et al. 2014) 32. (Merah and Djazouli 2016) 33. (Tabanca et al. 2010) 34. (Aihetasham et al. 2017) 35. (Mullin et al. 1991) 36. (Padin et al. 2013) 37. (Macedo et al. 1997) 38. (Ahmed et al. 2015) 39. (Vukajlović et al. 2018) 40. (Khater and Khater 2009) 41. (Jbilou et al. 2008) 42. (Sivaraman et al. 2014) 43. (Pavela 2009) 44. (Liang et al. 2015) 45. (Hossain and Haque 2010) 46. (Meradsi and Laamari 2016) 47. (Guarrera 1999) 48. (Ebadollahi 2011) 49. (Pavela 2004) 50. (Kumar et al. 2011) 51. (Arnoabeng et al. 2018) 52. (Koul et al. 2008) 53. (Momen et al. 2014) 54. (Amoabeng et al. 2013) 55. (Regnault-Roger et al. 2004) 56. (Lee et al. 2004) 57. (Ahmed et al. 2011) 58. (Lee et al. 2000) 59. (Sibul et al. 2001) 60. (Pelah et al. 2002) 61. (Morimoto et al. 2002) 62. (Akhtar and Isman 2004) 63. (Kozawa et al. 1982) 64. (Boussaada et al. 2008) 65. (Yeom et al. 2015) 66. (Guillet et al. 1997) 67. (Raghavendra et al. 2013) 68. (Larocque et al. 1999) 69. (Kim et al. 2003)

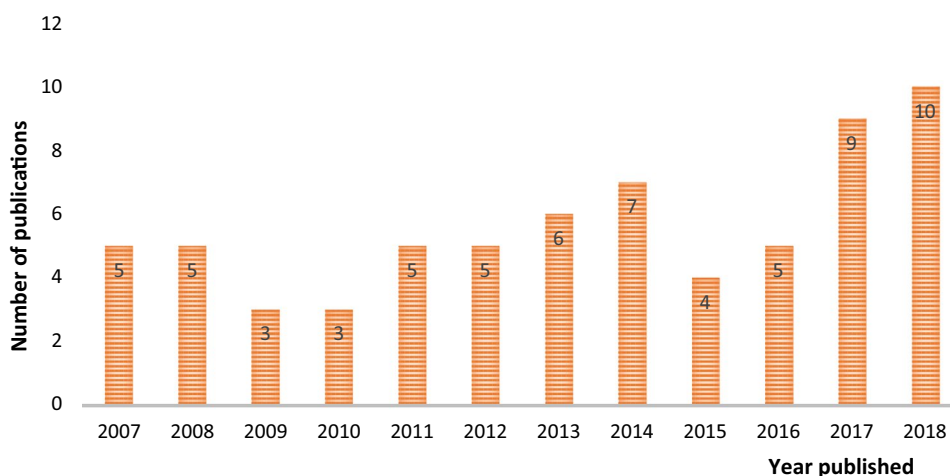
Reference for tested plant but less efficacious/no activity: a. (Mohankumar et al. 2016) b. (Pavela 2010) c. (Pascual-Villalobos and Robledo 1999) d. (Pavela 2009) e. (Alexenizer and Dorn 2007) f. (Pavela 2011) g. (Kim et al. 2003) h. (Moreira et al. 2007)

The Apiaceae

The Apiaceae (umbellifers) is the 16th largest angiosperm family with 442 genera and 3575 species in which most of the aromatic flowering plants are found (Christenhusz and Byng 2016). It has a global distribution and many species with both habitat manipulation and insecticidal activity

traits (Christenhusz and Byng 2016). Apiaceae species are annual, biennial or perennial herbs and woody shrubs and small trees that produce colorful inflorescences that secrete nectar attracting pollinators including bees, moths and beetles (Heywood et al. 2007). Their growth habit makes them agronomically suitable as habitat manipulation species (Fiedler et al. 2008). The flat headed morphology of their

Fig. 2 Temporal trend in published papers on habitat manipulation between 2007 and July 2018. Previously published papers on habitat manipulation (1989 to July 2006 were the subject of Fiedler et al. (2008))



inflorescence provides easy landing and access to nectaries for natural enemies encouraging visitation (Heywood et al. 2007).

Plants in the Apiaceae produce secondary metabolites including coumarins, monoterpenes and sesquiterpenes (Lee and Rasmussen 2000). Essential oils have been tested as being acaricidal (Attia et al. 2011), bactericidal (Glisic et al. 2007; Matasyoh et al. 2009) and for medicinal purposes (Lee and Rasmussen 2000; Maulidiani et al. 2014). Essential oils from Apiaceae species have been used against stored product pests including the bean weevil *Acanthoscelides obtectus* Say (Coleoptera: Bruchidae) (Regnault-Roger et al. 1993), the cigarette beetle *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae) and wheat flour beetle *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae) (Kim et al. 2003). Insecticidal activity against turnip aphids, *Lipaphis pseudobrassicae* (Davis) (Hemiptera: Aphididae), pea aphid, *Acyrtosiphon pisum* (Harris) (Hemiptera: Aphididae) and the green peach aphid, *M. persicae* has been reported (Dancewicz et al. 2012; Sampson et al. 2005).

The Asteraceae (Compositae) family

The Asteraceae (daisy) is the second largest plant family after Orchidaceae (Stevens and Davis 2001) with 24,700 species in 1623 genera and a worldwide distribution (Christenhusz and Byng 2016). Asteraceae species have clusters of inflorescence that appears to be a single flower often referred to as head (Schmid 2004). The entire flower head moves towards the direction of the sun and that maximizing reflectivity which may enhance the attraction of pollinators and other beneficial insects (Schmid 2004), which along with their growth habit makes them largely acceptable for habitat manipulation (Altieri et al. 2005). A larger number of plants in the family are herbaceous, with shrubs and trees rare (Okunade 2002). Species in the Asteraceae have

been exploited for their insecticidal activity against crop and storage pests (Gbolade et al. 2011) and also against several pathogenic organisms with success (Del-Vechio-Vieira et al. 2009; Senatore et al. 2004). The chemical composition of some species including *Ageratum conyzoides* L. (Asteraceae) has been well described (Chu et al. 2010; de Souza et al. 2009; Nenaah et al. 2015; Okunade 2002). The insecticidal activity of an aqueous extract of *A. conyzoides* has shown success rates comparable to chemical insecticides against diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) (Amoabeng et al. 2013; Bhathal et al. 1994).

The Lamiaceae

The Lamiaceae (mints and deadnettles) is characterised by many aromatic species (Heywood et al. 2007). The family is composed of 7530 species in 241 genera and globally distributed (Christenhusz and Byng 2016). The Lamiaceae includes trees, shrubs, subshrubs and herbs that are annuals or perennials (Harley et al. 2004). The Lamiaceae has a large variety of species composed of plants that may bloom early in the season (annuals) and those that would bloom late but will continue in bloom for longer periods (perennials).

Lamiaceae have been used for the provision of ecosystem services such as herbs and spices that provide antioxidants, flavours and food preservatives (Demo et al. 1998; Hossain et al. 2008; Vallverdu-Queralt et al. 2014). Secondary metabolites from the Lamiaceae have activity against human pathogenic organisms (Baydar et al. 2004; Karanika et al. 2001) and have been used for their insecticidal activity against domestic, storage and field crop pests. Extracts of *Origanum vulgare* L. demonstrated efficacy against *P. xylostella* and *Trichoplusia ni* Hübner (Lepidoptera: Noctuidae) in a laboratory bioassay (Akhtar and Isman 2004). *Ocimum gratissimum* L. oil and its constituents have fumigant and repellent activity against a

number of storage pests (Kim et al. 2003; Ogendo et al. 2008) as well as malaria vectors *Aedes aegypti* L. (Diptera: Culicidae) and *Culex quinquefasciatus* Say (Diptera) (Diptera: Culicidae) (Kamaraj et al. 2008).

Outlook and conclusions

The current review has shown that the most popular habitat manipulation plant families are among the top plant families that have also been exploited for their insecticidal activity. Accordingly, many of the species that have shown benefit in habitat manipulation have unrecognized additional value; they could be exploited for the secondary use of harvesting plant parts to produce botanical insecticides. Habitat manipulation and plant extracts make a potentially effective combination due to the largely benign nature of both tactics on natural enemies. It is widely acknowledged that tactics that can provide multiple ecosystem services may prove effective and most likely to be adopted than are tactics that provide single benefits in isolation (Gentz et al. 2010). The tractability of combining two tactics depends on the effect of each individual tactic on natural enemy populations. For example, an inherent toxicity to natural enemies by a biopesticide would be antagonistic towards conservation biological control. However, a combination in which both botanicals and habitat management do not have negative effects on natural enemies will likely result in additive or synergistic effect. A current study using six non-crop plants including *A. conyzoides* and *Tridax procumbens* (Asteraceae) with the same plant for habitat manipulation and plant extracts was successful and cost-effective in managing pests of cabbage (Amoabeng et al. unpublished data).

Much is currently not known about why some plant families have many species useful for both habitat manipulation (pollen and nectar producing) and botanical insecticides. However, there could possibly be link between plants with insecticidal activity being attractive to predators and parasitoids. Secondary metabolites occur in the pollen and nectar and, at optimum concentration, benefit pollinators, parasitoids and predators for example in mediating plant–pollinator interaction, protecting nectar from robbery and other microbial functions such as preserving nutrients in nectar from degradation and reducing diseases in pollen and nectar beneficiaries (Stevenson et al. 2017). It is possible that some plant species in the families producing nectar and with insecticidal activity have common ecological characteristics. According to Campbell (2015), plant defence against herbivores and reproduction do not evolve separately but may have reciprocal and interactive effects on each other. Our hope is that this review will constitute the first step in uniting the separate fields of botanical insecticides and nectar

plants for biocontrol enhancement. Future experimental and meta-analysis papers will be required to identify mechanistic patterns that underpin dual utility.”

Realising dual or multiple ecosystem services from habitat manipulation is an ambitious call to rapidly restore some lost ecosystem services, but there are other precedents that suggest it is possible, e.g., Davis et al. (2012). Finney et al. (2017) studied the delivery of eight ecosystem services including pests suppression, nitrogen supply, weed suppression among others from ten cover crops. The study showed that where all the plant species supplied biomass, suppressed weeds and retained nitrogen, there were trade-offs between other ecosystem services among some species. This underscores the need to develop clear understanding of the intended services to be delivered and selection of plant species (Gurr et al. 2017). Ultimately, however, the present review suggests that further research is justified to fully explore scope for using habitat manipulation plants as a source of botanical insecticides. Among the research priorities is field work to assess the phenological and practical issues around dual use. For example, habitat manipulation plants normally need to be established early in the crop calendar so they are blooming early in the season, providing resources to natural enemies and thereby prevent pest population build-up. This may be compatible with dual use because harvesting plant parts such as foliage or seed pods for botanical insecticide production could be later in the season on a “needs basis” to deal with uncontrolled pest build-up, should biological control falter. On a wider time scale, habitat manipulation plants could be harvested at the end of the growing season and stored for later processing into botanical insecticides for use in a subsequent crop. In addition, ‘non-crop’ species may be cultivated on any spare land and harvested for the preparation of botanical insecticides. This would avoid potential disruption of the conservation biological control aspect of the program and might further generate income to individuals who would cultivate plants for the extraction of botanical insecticides. Such low-tech approaches are particularly appropriate for developing country agriculture.

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