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REVIEW

The effects on terrestrial invertebrates of reducing pesticide inputs in arable crop edges: a meta-analysis

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Summary

1. There is an increasing awareness of the need to evaluate critically the effectiveness of environmental conservation measures, and to ensure that agri-environment policies are based on the best available scientific evidence.

2. A systematic review and meta-analysis investigated the impact of pesticide restriction in arable crop edges on naturally occurring terrestrial invertebrates. Twenty-three relevant experimental studies yielded 1094 pesticide contrasts. A standardized effect size (Hedges' g) could be calculated for 685 of these.

3. Empirical data were available for 12 broad types of pesticide manipulation in crop edges. The majority of the data concerned the exclusion or selective use of herbicides. No reliable information was available on the ecological consequences for naturally occurring arthropods of excluding fungicides or insecticides separately from crop edges.

4. Studies have focused on Carabidae, Heteroptera, Staphylinidae, Lepidoptera and grouped chick-food insects. Abundance of Heteroptera was up to 12·9 times higher where pesticide use was restricted. For other invertebrates, restricted use of pesticides generally either increased abundance or had no impact. Only two species exhibited a significant decrease in abundance.

5. Restricting pesticide use in crop edges in most cases did not significantly affect Carabidae. This might be an artefact of the sampling method, which predominantly involved pitfall trapping.

6. Generalization of the findings is hindered by ambiguous reporting in the primary studies. In most (20 out of 23) studies, the possibility of confounding between pesticide and fertilizer inputs could not be discounted.

7. *Synthesis and applications*. Meta-analysis confirms that restriction of pesticide inputs in crop edges benefits arthropod populations at the edges of arable fields. However, an assumption in risk assessment that such benefits extend to invertebrate populations in adjacent sprayed areas is not supported. Moreover, the generality of the effects within crop edges is limited mainly to herbicides. This review highlights a lack of information on the ecological consequences of excluding insecticides and fungicides from crop edges, and identifies a need to improve the clarity of reporting in agro-ecology studies.

Key-words: agri-environment schemes, buffer zones, chick-food insects, conservation headlands, field margins, herbicides, Heteroptera, risk mitigation

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Introduction

Since the late 1970s, exclusion, or selective use of pesticides within crop edges, has been used as a means to mitigate the risk of pesticides to wildlife in arable fields and to reduce 'off-crop' risks caused by pesticide movement into field boundaries or adjacent habitats such as watercourses. The conservation functions and ecological impacts of pesticide exclusion from crop edges have been considered at four major symposia in the UK (Way & Greig-Smith 1987; Boatman 1994; Haycock *et al.* 1997; Boatman *et al.* 1999) and in ad hoc European workshops (Jörg 1995).

Herbicide-free field-edge strips (herbizidfrei Ackerrandstreifen) were initiated in Germany in 1978 to protect native arable flora in crop edges (Schumacher 1984). In southern England during the early 1980s, the Game Conservancy Trust developed conservation headlands (the exclusion, or selective use, of herbicides and insecticides on arable crop edges) to assist the survival and breeding success of grey partridge populations (Sotherton, Boatman & Rands 1989). Ackerrandstreifen and conservation headlands are regarded as successful contributions to the conservation of farmland wildlife (Schumacher 1987; Boatman 1998) and have been incorporated as management options within agri-environment schemes (Kleijn & Sutherland 2003). Unsprayed or selectively sprayed crop edges have been implemented in at least 13 European countries (de Snoo & Chaney 1999; Fry & Rinde 2002).

Application of some pesticides to arable crop edges may be prohibited as a statutory condition of use. In Britain, for example, sprayed applications of most synthetic pyrethroid and organophosphate insecticides and some other broad-spectrum pesticides are not permitted on the outermost 6 m of arable crops in summer, to reduce the risk to non-target arthropods (Campbell 1995). An assumption in risk assessments for the regulatory approval of pesticides within Europe is that protection of invertebrates in unsprayed crop edges may assist recovery of invertebrate populations in the sprayed area of fields (Forster & Rothert 1998).

Recently, the ecological effectiveness of some agri-environment schemes has been called into question (Kleijn *et al.* 2001, 2003), highlighting the need for a critical and systematic approach to evaluate the effectiveness of conservation practices (Sutherland *et al.* 2004; Stewart, Coles & Pullin 2005).

A systematic review was conducted to address the following questions. (i) Which types of pesticide manipulation in crop edges have the largest impact on invertebrate populations? (ii) Which invertebrate taxa respond most strongly to crop-edge pesticide manipulation, and do the responses differ between beneficial and pest species? (iii) Can unsprayed crop edges assist invertebrate population recovery in adjacent sprayed areas?

These questions were addressed using meta-analysis to synthesize quantitative information from independent studies. Meta-analysis can reduce the subjectivity of interpretation by applying a consistent analytical approach across all studies, and can produce estimates of the magnitude of treatment effects and their certainty (confidence limits), which is preferable to the use of significance tests (Johnson 1999).

Methods

SEARCH STRATEGY

A systematic review of studies on the ecological effects of pesticide manipulation at crop edges was carried out using six steps: (i) hand searching of relevant research papers held at Southampton University and the library of the Game Conservancy Trust; (ii) literature searches using online databases (CAB Abstracts, BIOSIS Previews and Web of Knowledge 1966 to August 2005); (iii) searches of the tables of contents of relevant agro-ecology journals; (iv) internet searches using Google™; (v) follow-up of relevant citations; and (vi) consultation with experts in agro-ecology world-wide to establish the extent of relevant ongoing and unpublished research.

INCLUSION CRITERIA

Information was considered relevant if it described or discussed the impact of any type of pesticide manipulation in crop edges on naturally occurring terrestrial invertebrates. Data were excluded if they were obtained from bioassays with confined test organisms or from pesticide manipulation in non-crop field edges (e.g. uncropped or sown 'wildlife' strips). For inclusion in the quantitative analysis (see below), a study had to contain: (i) at least two levels of pesticide input (experimental treatments) within comparable arable crop edges such that differences in pesticide inputs were not confounded with other variables; and (ii) at least three spatial replicates of the experimental treatments.

DATA EXTRACTION

For each pesticide treatment, the sample size, mean and SD of the invertebrate catch were extracted, together with information on the pesticide treatment comparison, invertebrate species or groups monitored and study design. If necessary, SD were calculated from other statistics.

DATA ANALYSIS

The consequences of pesticide manipulation are straightforward to interpret if an increase in the abundance or richness of beneficial or non-target species is assumed to represent a desirable conservation outcome, whereas an increase in the abundance of pest species would be undesirable. A relevant and widely used effect metric based on the difference between two treatment means is the standardized mean difference, Hedges' g. This effect metric provides a scale-independent estimate of the magnitude of treatment effects, weighted to account for unequal variances and sample sizes, and is appropriate for combining effects estimates from independent studies (Gurevitch & Hedges 1999).

Here, Hedges' g is defined as the difference between the means of the two pesticide comparisons for a given pesticide contrast, here $\bar{X}_{reduced}$ (the reduced or selective pesticide input treatment) and $\bar{X}_{reference}$ (the reference, higher pesticide input), divided by the pooled SD and multiplied by a correction factor for small and unequal sample sizes (Gurevitch & Hedges 2001):

$$g = \frac{\bar{X}_{reduced} - \bar{X}_{reference}}{\text{pooled SD}} \times \left(1 - \frac{3}{4m-1}\right)$$

and

$$\text{pooled SD} = \sqrt{\frac{(n_{reduced}-1)\text{SD}^2_{reduced} + (n_{reference}-1)\text{SD}^2_{reference}}{n_{reduced} + n_{reference} - 2}}$$

where $m = n_{reduced} + n_{reference} - 2$. Hedges' g was not calculated if the available treatment means were based on fewer than three samples. Estimates of Hedges' g with 95% confidence intervals were obtained separately for each type of pesticide contrast in mixed-effects models, using the software program Comprehensive Meta-Analysis (Version 2, Biostat®, Englewood, NJ). A mixed-effects model combines the advantages of fixed- and random-effects models and is appropriate for analysing groups of effects data where effects may not be homogeneous within groups, or where all the data are restricted to one group (Gurevitch & Hedges 2001). Homogeneous groups were defined as those for which the heterogeneity statistic, Q, was not significant ($P > 0{\cdot}05$). For each type of pesticide contrast, estimates of Hedges' g were obtained for up to three invertebrate taxonomic levels: (i) an overall effect for the individual taxa pooled; (ii) the total catch; and (iii) taxonomic richness.

If Hedges' g was not calculable, the raw difference in abundance or richness was calculated instead ($\bar{X}_{reduced} - \bar{X}_{reference}$). For each type of pesticide contrast, a binomial test was used to examine whether the proportion of positive effects (i.e. where $\bar{X}_{reduced} > \bar{X}_{reference}$) could be explained by chance (excluding cases with a raw difference of zero).

A prerequisite of meta-analysis is that the primary data are from independent studies. Data that were clearly not independent were either pooled before calculating the effect size or analysed and reported separately. Where data for a given taxonomic group were collected from the same location on several sampling dates within a year, the overall mean (abundance, total or richness) for each treatment was calculated first, to provide one estimate of effect size. However, data from consecutive years were considered independent because most studies were conducted with a relatively long gap between samplings in consecutive years, and multiyear studies tended to employ different fields, crops and/or sampling locations from one year to the next, which would dilute any temporal dependence of invertebrate responses.

Results

Thirty studies have investigated the effects of crop-edge pesticide manipulation on naturally occurring invertebrates (Table 1). In all cases the monitored invertebrates were arthropods. The experimental designs of the studies are summarized in Table S1 (see the supplementary material).

DATA INCLUSION

Of the 30 studies, seven were excluded from quantitative analysis (Table 1). These were behavioural observations (which cannot easily be equated with positive or negative effects) (studies 3 and 5), unreplicated studies (17 and 22), reports that did not provide relevant quantitative information (12 and 30) and one study with an experimental design that left an unrealistically large area of the field unsprayed (18). In three studies (1, 2 and 6), pesticide treatments were not independent of spatial location (as each treatment was assigned to a spatially discrete set of fields). These studies were included separately in the analysis for comparison of effect sizes, as they were among the largest studies in spatial scale (with up to 33 fields).

Fertilizers may have a pronounced impact on crop vegetation (Kleijn & van der Voort 1997) and arthropod communities (Siemann 1998), but only three studies (7, 16 and 20) reported methods clearly enough to confirm that the pesticide treatments were not confounded with fertilizer use. Effect sizes were therefore calculated separately for studies in which confounding did not occur and for those in which confounding cannot be discounted.

Hedges' g was calculable in 15 of the included studies. In the remaining eight studies, only raw treatment differences could be calculated (Table 1). In some studies (19, 20, 21 and 28) both Hedges' g and raw differences were calculated for different subsets of the data. Together, the included studies yielded 1094 pesticide contrasts, with Hedges' g calculable for 685 of these (Table 2).

PESTICIDE TREATMENTS

Twelve types of experimental pesticide comparison in crop edges were identified (Table 2). Information was available for fungicides (F), herbicides (H) and insecticides (I) but not for other pesticide modes of action (e.g. acaricides, molluscicides and nematicides). In some cases, pesticide inputs were reported without detail, as being 'typical', 'conventional' or 'normal' for the given agricultural scenario (here designated NORM), as conservation headlands (CONS) or as pooled combinations of F, H, FH or FHI (here designated VARIOUS). Of the 23 included studies, relatively few identified the individual pesticide active ingredients (six studies), the number of individual pesticide applications (five studies), the dates of pesticide applications (three studies) or the application rates used (five studies). Only three studies provided all of this information. The majority of pesticide treatment contrasts involved either the exclusion of multiple pesticide classes or the exclusion of herbicides. No information was available

Table 1. Studies of pesticide manipulation in arable crop edges identified in a systematic review. Where the effect size (Hedges' *g*) could not be calculated, the raw difference between treatment means (Raw diff) was used (details in text)

Study type	Study no.	Principal references	Analysis
Conservation headlands (CH), southern England	1	Rands (1985)	Hedges' *g*
	2	Moreby (1995)	Hedges' *g*
	3	Dover, Sotherton & Gobbett (1990), Dover (1993)	Excluded*
	4	Cowgill, Wratten & Sotherton (1993)	Raw diff†
	5	Dover (1997)	Excluded*
	6	Rands & Sotherton (1986)	Raw diff†
	7	Chiverton & Sotherton (1991)	Hedges' *g*
	8	Moreby (1994, 1997), Moreby & Southway (1999)	Hedges' *g*
CH, central and eastern England	9	ADAS (1997)	Hedges' *g*
	10	Cardwell, Hassall & White (1994), Hassall *et al*. (1992), White & Hassall (1994)	Raw diff†
	11	Hawthorne (1994, 1995), Hawthorne & Hassall (1995)	Raw diff†
	12	Allen, Gundrey & Gardner (2001)	Excluded‡
	13	Gardner *et al*. (2001b)	Raw diff†
	14	Gardner *et al*. (2001a)	Raw diff†
	15	Reynolds (2001)	Hedges' *g*
CH, Scotland	16	Hughes (1999)	Hedges' *g*
Insecticide exclusion, southern England	17	Holland, Winder & Perry (1999, 2000)	Excluded§
	18	Tones *et al*. (2000)	Excluded¶
The Dutch Field Margin Project, the Netherlands	19	de Snoo, van der Poll & de Leeuw (1995)	Hedges' *g*
	20	de Snoo & de Leeuw (1996)	Hedges' *g*
	21	de Snoo, van der Poll & Bertels (1998)	Hedges' *g*
Herbizidfrei Ackerrandstreifen (herbicide-free crop edges), Germany	22	Raskin, Glück & Pflug (1992), Raskin (1994)	Excluded§
	23	Felkl (1988)	Hedges' *g*
	24	Kühner (1988), Storck-Weyhermüller (1988), Welling, Pötzl & Jürgens (1988), Vieting (1988)	Hedges' *g*
	25	Welling (1990), Storck-Weyhermüller & Welling (1991), Welling *et al*. (1990, 1994)	Hedges' *g*
Crop-edge studies in Scandinavia	26	Hald *et al*. (1988) (Denmark)	Raw diff†
	27	Hald *et al*. (1994) (Denmark)	Raw diff†
	28	Helenius (1994), Nissinen (1999) (Finland)	Hedges' *g*
	29	Chiverton (1993, 1994, 1995, 1999) (Sweden)	Hedges' *g*
	30	Fry & Rinde (2002) citing Framstad & Lid (1998) (Norway)	Excluded‡

*Behavioural observations (see text).
†Relevant mean, SD, or *N* unavailable (or ambiguous).
‡No relevant empirical data presented.
§Unreplicated.
¶Limitation of study design (see text).

on the separate exclusion of fungicides or insecticides (Table 2).

To report pesticide contrasts consistently, the format 'reduced vs. reference' is used. For example, a fungicide-only treatment compared with a treatment containing both fungicides and herbicides is designated F vs. FH. Exclusion of all pesticides is designated ZERO (Table 2). The reference treatment in most cases probably had similar chemical inputs to the sprayed (interior) area of the field (details were rarely given).

RESPONSES OF ARTHROPODS IN CROP EDGES

The data comprised 30 higher taxa (family or above), representing 71 individual species, as well as other lower taxonomic groups. Most data were for Carabidae (35%), Heteroptera (19%), Staphylinidae (9%), Lepidoptera (7%), grouped chick-food insects (4%) and Diptera (3%). The most popular methods for sampling arthropod populations were portable suction devices (39% of samples), pitfall trapping (38%), sweep netting (10%) and visual observations (8%). The majority (93%) of Carabidae data were obtained using pitfall traps whereas all Heteroptera data were obtained using suction or sweep sampling. After the data have been grouped by taxon, pesticide contrast and study design (Figs 1–8), the resulting groups were in all cases homogeneous [the heterogeneity statistic (Q) was not significant ($P > 0{\cdot}05$) for any group with ≥ 2 Hedges' *g* data].

HETEROPTERA

Heteroptera data were available for six types of pesticide contrast. Hedges' *g* was significantly greater than zero

Table 2. Availability of effects data for pesticide treatment comparisons in arable crop edges. F, fungicides; H, herbicides; I, insecticides; ZERO, unsprayed; CONS, conservation headland pesticide inputs (usually *sensu* Sotherton, Boatman & Rands 1989); NORM, normal (typical or conventional) pesticide inputs (details unspecified); VARIOUS, pooled combinations of herbicides, fungicides and/or insecticides (details unspecified). The source studies are summarized in Table 1 and Table S1 (see the supplementary material). Positive effects on invertebrates are defined as those where mean abundance or taxonomic richness in the reduced-input treatment exceeds that in the reference (higher-pesticide input) treatment. Asterisks indicate the binomial probability that the observed proportion of positive effects would be expected by chance (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$). Study design indicates: a, pesticide and fertilizer were not confounded; b, pesticide and fertilizer might have been confounded; c, large-scale studies in which pesticide treatments were not spatially independent

				No. of effects data (no. of positive effects)	
Pesticide treatment type	Treatment comparison (reduced vs. reference)	Studies	Design	Hedges' *g* calculable	Hedges' *g* not calculable
Herbicide exclusion	F vs. FH	7, 16	a	71 (67)***	
		8, 24, 25	b	152 (97)**	7 (5)
	ZERO vs. H	8, 23, 25, 28	b	168 (119)***	2 (1)
Herbicide or herbicide and insecticide exclusion	ZERO vs. H or HI	28	b	36 (27)**	5 (4)
Fungicide and herbicide exclusion	ZERO vs. FH	26	b		3 (3)
Herbicide and insecticide exclusion	F vs. FHI	20	a	42 (36)***	10 (9)*
		19, 21	b	116 (95)***	
	ZERO vs. HI	19	b	32 (26)**	198 (102)
Fungicide, herbicide and insecticide exclusion	ZERO vs. FHI	26, 29	b	8 (8)**	32 (29)***
Other unsprayed edges	ZERO vs. NORM	27	b		
	ZERO vs. VARIOUS	1	b,c	4 (4)	110 (54)
Conservation headlands	CONS vs. FH	4, 11	b		18 (18)***
	CONS vs. FHI	2, 6	b,c	45 (30)*	24 (19)**
	CONS vs. NORM	9, 10, 13, 14, 15	b	11 (5)	

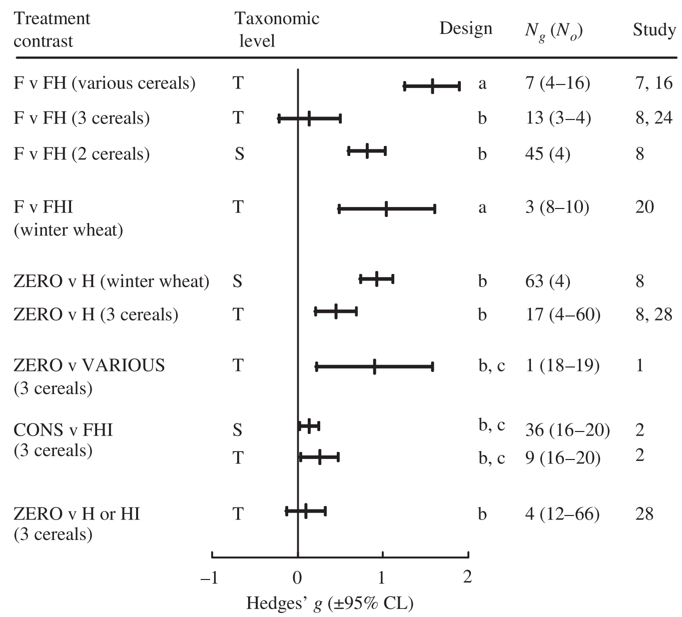

Fig. 1. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on Heteroptera within crop edges (details of the pesticide contrasts are given in Table 2 and the text). Mixed models based on N_g independent estimates of Hedges' *g*, each of which comprised N_o original data per treatment. Effect sizes are for individual species (S) or total Heteroptera counts (T). Positive effects indicate higher abundance in the reduced pesticide input treatment. An overall effect size for all contrasts is not presented, as the data are not independent. Design indicates: a, pesticide and fertilizer were not confounded; b, pesticide and fertilizer might have been confounded; c, large-scale studies in which pesticide treatments were not spatially independent.

in seven of 10 comparisons (Fig. 1). All pesticide contrasts involved exclusion of herbicides; the effect of excluding fungicides or insecticides in isolation could not be determined. Exclusion of herbicides, alone or with fungicides or insecticides, increased Heteroptera abundance by up to 12·9 times (log ratio 2·56) and in some cases approximately doubled taxonomic richness (log ratio 1·9–2·1).

HOMOPTERA

Effects of pesticide restriction have been less well-studied for Homoptera and were not statistically significant. An exception was a significant reduction in the abundance of cereal aphids in the edge of winter wheat crops when herbicides were excluded (Fig. 2). These data were from one study only, in which the abundance of aphids was approximately 50% higher in the herbicide-sprayed crop edges.

CHICK-FOOD INSECTS

'Chick-food insects' refers to the grouping together of Lepidoptera and Symphyta larvae as well as some Coleoptera families, which may differ between studies (Rands 1985; Chiverton & Sotherton 1991; Helenius 1994; Hughes 1999; Moreby & Southway 1999). The abundance of chick-food insects was increased significantly in seven

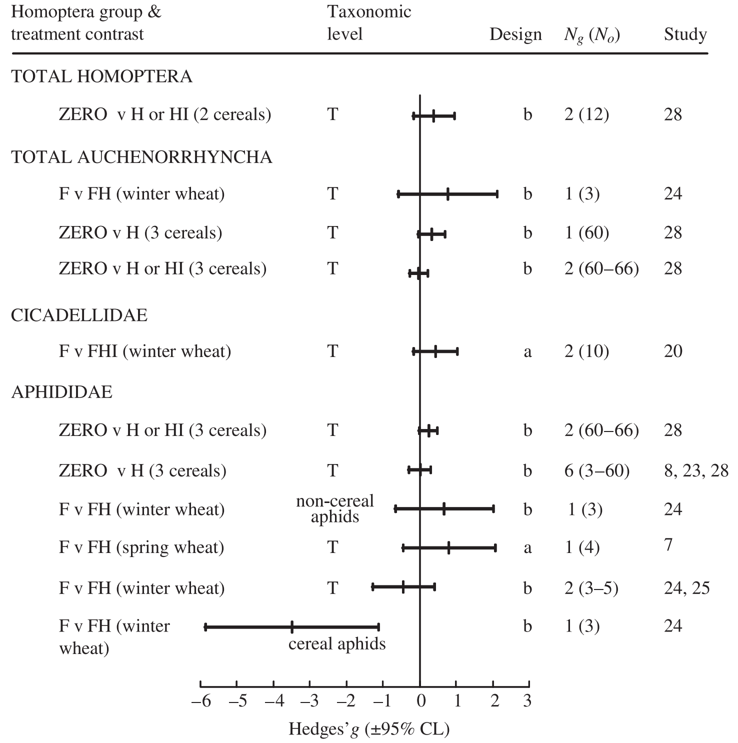

Fig. 2. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on Homoptera within crop edges (details as in Fig. 1). Effect sizes are for total Homoptera counts (T) or aphids. An overall effect size for all contrasts is not presented, as the data are not independent.

out of 15 comparisons, by four types of pesticide restriction, involving either exclusion of herbicides or the joint exclusion of herbicides and other pesticides (Fig. 3). The largest effect was for grouped chick-food insects, with an increase of abundance by up to 2·7 times (log ratio 0·30–0·10). For Lepidoptera adults, only the joint exclusion of herbicides and insecticides (F vs. FHI) could be evaluated, which approximately doubled abundance, species richness and total Lepidoptera catches (log ratio 1·7–2·1). Abundance of Symphyta larvae was approximately doubled (log ratio 0·83) by the exclusion of herbicides (F vs. FH), but in five other comparisons Hedges' *g* for Symphyta adults and Lepidoptera larvae did not differ significantly from zero (Fig. 3).

CARABIDAE

Responses of Carabidae could be examined for five types of pesticide contrast (Fig. 4). Effects of pesticide exclusion on carabid abundance were positive and significant in three out of 16 comparisons, but in most cases did not differ significantly from zero. The positive effects reflected an increase of abundance by 1·1–1·8 times (log ratio 0·10–0·56) and involved exclusion of herbicides, either alone (F vs. FH) or jointly with insecticides (ZERO vs. HI or F vs. FHI).

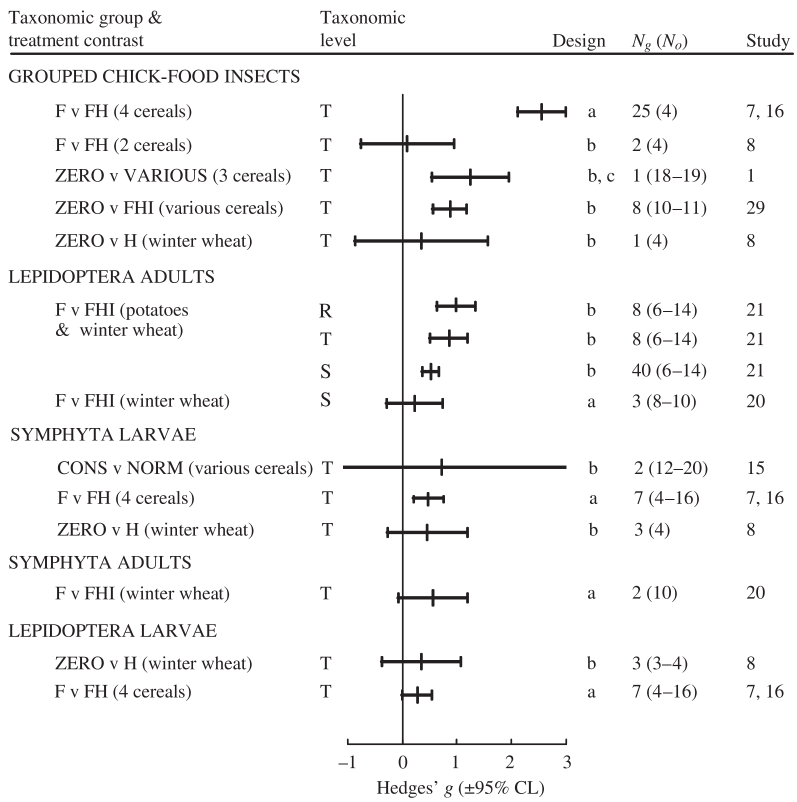

Fig. 3. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on chick-food insects within crop edges (details as in Fig. 1). Effect sizes are for individual species (S), total counts (T) or taxonomic richness (R). An overall effect size for all contrasts is not presented, as the data are not independent.

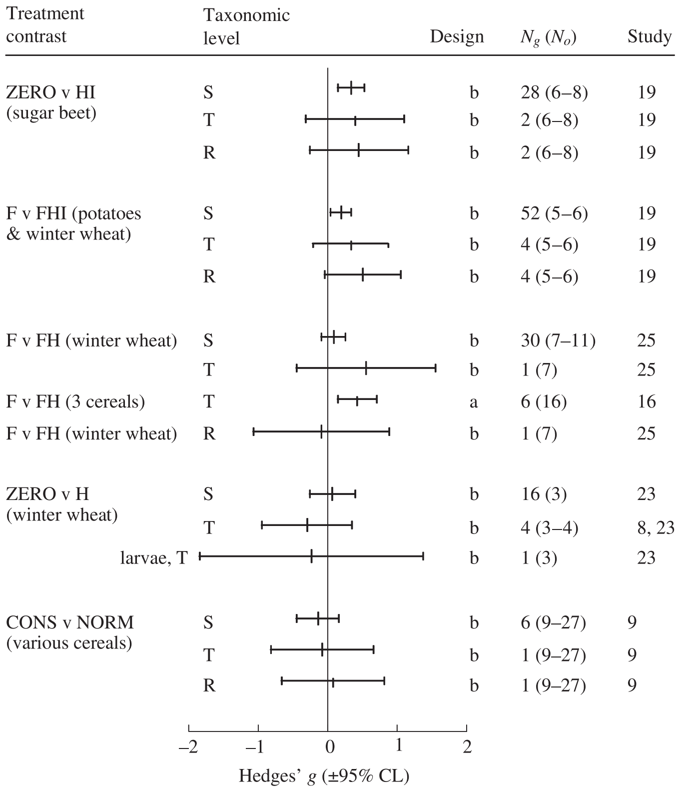

Fig. 4. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on Carabidae within crop edges (details as in Fig. 1). Effect sizes are for individual species (S), total counts of adults (T), total counts of larvae (larvae, T) or taxonomic richness (R). An overall effect size for all contrasts is not presented, as the data are not independent.

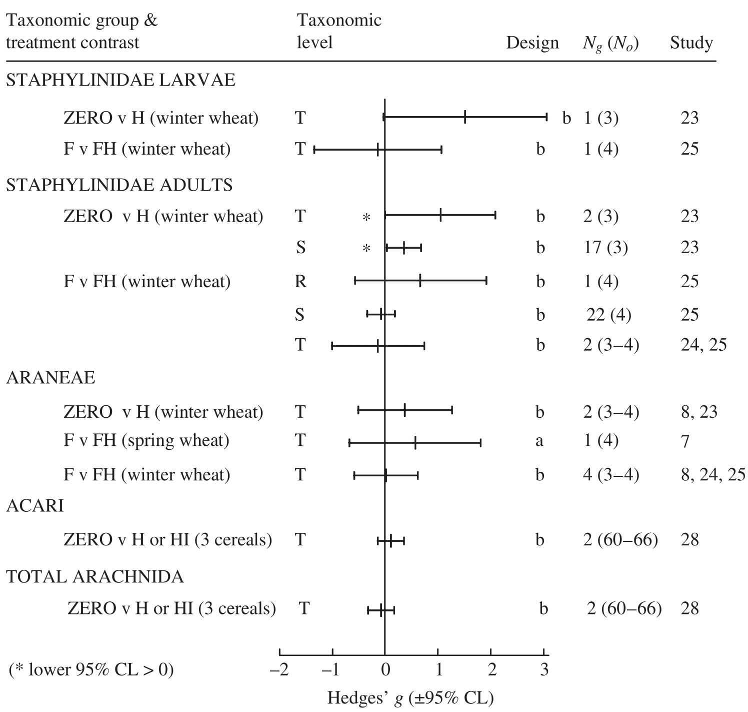

Fig. 5. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on Staphylinidae and Arachnida within crop edges (details as in Fig. 1). Effect sizes are for individual species (S) or total counts (T). An overall effect size for all contrasts is not presented, as the data are not independent.

STAPHYLINIDAE

Exclusion of herbicides (ZERO vs. H or F vs. FH) resulted in either a significant increase in staphylinid abundance (by a factor of 1·2–1·4; log ratio 0·18–0·34) or had no significant effect (Fig. 5). No information was available for Staphylinidae on the effects of other types of pesticide exclusion.

OTHER COLEOPTERA

The abundances of Chrysomelidae, Coccinellidae (adults), Curculionidae, Nitidulidae and total catches of Coleoptera were in some, but not all, cases increased significantly by exclusion of herbicides, either alone (F vs. FH) or combined with the exclusion of insecticides (F vs. FHI) (Fig. 6). Nitidulidae abundance was nine times higher in crop edges without herbicides and insecticides (log ratio 2·19) but the data were from only one study. Increases of a factor of 3·8 for Chrysomelidae (log ratio 1·34) and 4·8 for Coccinellidae adults (log ratio 1·57) occurred in some cases, whereas in other cases effects of pesticide exclusion were not significantly different from zero for these families.

ARACHNIDA

None of the groups of Arachnida studied (Araneae, Acari or the total Arachnida) were influenced significantly by exclusion of herbicides (ZERO vs. H or F vs. FH) (Fig. 5). No information was available for Arachnida on the effects of other types of pesticide exclusion.

OTHER ARTHROPODS

With the exception of Neuroptera and Diptera, effects of pesticide restriction on other arthropods in crop edges did not differ significantly from zero (Fig. 7). For Neuroptera and Diptera, in some cases abundance was increased significantly by the exclusion of herbicides and insecticides (F vs. FHI) and for Diptera also by the exclusion of herbicides alone (ZERO vs. H).

PATTERNS IN RAW DIFFERENCES

For the majority of comparisons that had 10 or more data, both Hedges' *g* and raw differences indicated that the frequency of positive effects was greater than would be expected by chance (binomial test; Table 2). None of the comparisons yielded a lower frequency of positive effects than would be expected by chance.

VARIATION OF EFFECTS WITH SPECIES, DISTANCE INTO CROP, CROP TYPE AND EDGE WIDTH

In cases where effects of pesticide contrasts were significant for families (Carabidae, Staphylinidae) or orders (Diptera, Heteroptera), not all individual

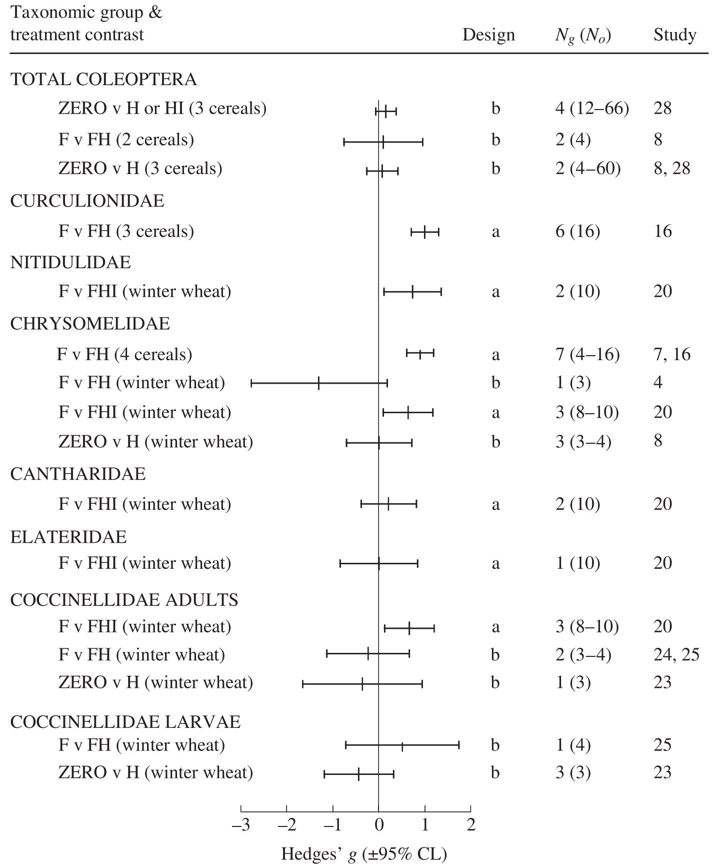

Fig. 6. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on other Coleoptera groups within crop edges (details as in Fig. 1). Effect sizes are for total counts. An overall effect size for all contrasts is not presented, as the data are not independent.

species or lower taxa exhibited the same response. For Carabidae, Staphylinidae, Heteroptera and Diptera, effects were significant for a minority of species or groups, whereas for Lepidoptera six out of seven species examined exhibited a significant positive effect. The Carabidae exhibiting the largest effects of herbicide exclusion were herbivorous species (*Amara* spp. and *Harpalus* spp.) (see Figure S1 in the supplementary material).

Only one of the studies for which Hedges' *g* could be calculated investigated effects of crop-edge pesticide restriction on arthropods in the adjacent sprayed crop, up to 50 m from the field boundary (study 2; studies numbered according to Table 1). Effects of the CONS vs. FHI treatment on Heteroptera were significantly greater than zero only within the 6 m-wide crop edge itself (Fig. 8). Another study (11) investigated effects of a conservation headland (CONS vs. FH) on aphids at distances up to 64 m from the field boundary, but mean raw differences in abundance provided no evidence for an effect at any of the sampling distances (ranges of the raw mean differences included zero for all comparisons). Carabidae were monitored in the same study, but results were available for only two replicates of each treatment. A third study (26) investigated effects of ZERO vs. FHI crop-edge pesticide treatments on arthropods in a cereal field up to 106 m from the field boundary, but without replication. In a fourth study (20), aphids were restricted to unsprayed field edges. Another study used directional barrier traps to investigate movement of Carabidae in arable field margins (Hawthorne 1994; Hawthorne, Hassall & Sotherton 1998) but these did not demonstrate dispersal from a conservation headland into an adjacent conventionally treated crop. These studies provide no conclusive evidence that manipulation of pesticide inputs within crop edges would affect invertebrate abundance, or population recovery (Forster & Rothert 1998), in the adjacent sprayed areas of fields.

The data were dominated by winter wheat (52%), mixed cereals (19%), spring barley (14%) and potato (5%). In most studies that involved several crops, the crop type was confounded with the year, geographical location and/or pesticide inputs, or the data were pooled across crops. The influence of crop type could be compared only for two types of herbicide and insecticide exclusion: ZERO vs. HI in autumn and winter cereals (study 29, chick-food insects) and F vs. FHI in winter wheat and potatoes (studies 19 and 21; Carabidae and Lepidoptera). In these studies, Hedges' *g* did not differ significantly between crop types. However, for Carabidae the pooled species effect was significantly greater than zero only for winter wheat (see Table S2 in the supplementary material).

The most frequently studied widths of the crop edge reported were 6 m (62% of the data), 3 m (13%), 5 m (9%) and 8–10 m (6%). Only one study (20) investigated the effects of pesticide exclusion (herbicides and insecticides; F vs. FHI) in crop edges of different widths (3 m and 6 m) such that edge width was not confounded with other variables. Effect sizes could be calculated for each width for Chrysomelidae, Coccinellidae, Heteroptera, Neuroptera and Syrphidae (in all cases total catches of adults). Hedges' *g* for Heteroptera was significantly greater than zero in the 6-m wide edge but not the 3-m wide edge. No other significant effects were observed among these taxa, and ranges (95% confidence limits) of Hedges' *g* for 3 m and 6 m widths overlapped in all cases (see Table S3 in the supplementary material).

Discussion

Given the lack of data on individual chemicals, this review focuses on pesticide classes (fungicide, herbicide and insecticide) rather than individual active ingredients or products. The findings can be generalized for several types of herbicide exclusion, but not for individual fungicides and insecticides. It is important to bear in mind that the external validity of pesticide contrasts in some cases is limited to certain taxa; the pesticide contrast CONS vs. FHI, for example, has only been evaluated for Heteroptera, whereas F vs. FH data are available for nearly 30 arthropod groups. To generalize

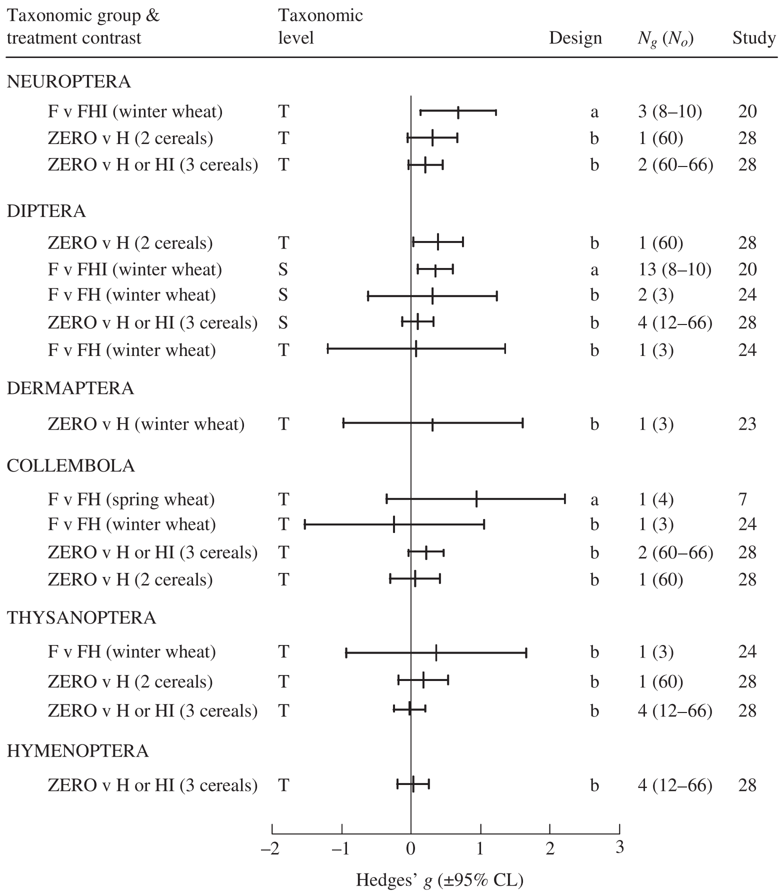

Fig. 7. Pesticide treatment effect sizes (Hedges' *g*) for effects of contrasting pesticide inputs (reduced vs. reference) on other arthropod groups within crop edges (details as in Fig. 1). Effect sizes are for individual taxa (S) or total counts (T). An overall effect size for all contrasts is not presented, as the data are not independent.

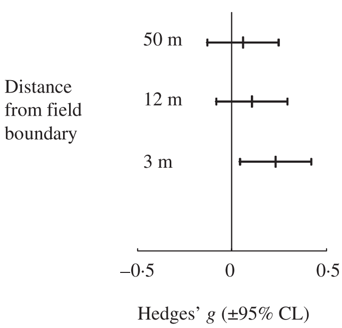

Fig. 8. Pesticide effect size (Hedges' *g*) for Heteroptera in cereals at three sampling distances from the field boundary (CONS vs. FHI, study 2; Moreby 1995). The overall effect size at each distance is calculated from 12 independent estimates of Hedges' *g*, each comprising 16–20 original data per treatment (mixed model).

the effects of pesticides, in most studies an assumption would have to be made that pesticide and fertilizer inputs were not confounded. A strict meta-analysis that excludes possible cases of fertilizer and pesticide confounding would only contain three studies.

The restriction of herbicides in crop edges clearly has a positive influence on arthropod populations. Most strongly affected are chick-food insects, Heteroptera and other herbivores (Chrysomelidae, Curculionidae and Nitidulidae). Positive effects on chick-food insects are not surprising, as this group includes selective herbivores (Symphyta and Lepidoptera larvae). Abundance of some predatory groups (Coccinellidae and Neuroptera) was also increased by pesticide exclusion, but in these cases insecticides as well as herbicides were excluded from the crop edges. Predators may be affected indirectly by the exclusion of herbicides alone, as a result of changes in their prey availability (Chiverton & Sotherton 1991). The data do not provide any evidence that pest species would be encouraged by excluding pesticides from crop edges, but information is only available on the responses of aphids to herbicide exclusion (studies 20 and 24). Cereal aphids (study 24) and the fungivorous Staphylinidae species *Micropeplus porcatus* (study 23) were the only taxa significantly reduced in abundance by herbicide exclusion; mechanisms to explain these negative effects have not been investigated.

The general lack of effects of herbicide restriction on Carabidae might be an artefact of the sampling method. The majority of data for Carabidae (studies 9, 19 and 25) were obtained by pitfall sampling. However, pitfall catches are influenced by vegetation density (Greenslade 1964), suggesting that this is an inappropriate method for sampling arthropods if vegetation density could vary among treatments, as would be expected with herbicide manipulations.

The overall lack of negative effects might indicate preferential reporting of positive effects in the primary studies. Several quantitative tests for publication bias are available but each has limitations (Gurevitch & Hedges 1999; Møller & Jennions 2001). The methodological approaches differed markedly between the primary studies (see Table S1 in the supplementary material), with some taxonomic groups and sampling methods represented only within certain pesticide treatment contrasts. This would preclude the use of funnel plots or related methods (Light & Pillemer 1984) to detect publication bias, as these assume data are selected randomly from similar studies. The binomial test provided no evidence that the proportion of positive effects differed consistently between unpublished reports or theses compared with peer-reviewed research papers, or between studies conducted at different geographical scales.

The largest effects of pesticide restriction might be expected where fully sprayed reference treatments comprising fungicides, herbicides and insecticides (FHI) were compared with unsprayed treatments (ZERO). In fact, the exclusion of herbicides alone (ZERO vs. H or F vs. FH) often had a greater effect than the exclusion of herbicides in combination with fungicides and/or insecticides. This probably reflects variability in the type, timing and application concentrations of individual chemical applications, which in most cases were not reported in the primary studies. Non-target arthropod populations can be strongly influenced by individual broad-spectrum herbicides (Chiverton & Sotherton 1991; Moreby & Southway 1999) whereas effects of insecticides vary from relatively small to large, depending upon the selectivity of the chemical (Moreby, Sotherton & Jepson 1997).

Overall (assuming that pesticide and fertilizer use were not confounded), meta-analysis confirms that restricting pesticide inputs to crop edges benefits arthropods but cautions against the generalization of effects except for herbicides. Risk mitigation benefits of excluding individual pesticides are not supported by the available data, but this reflects a shortage of evidence rather than clear evidence for a lack of benefits. To improve data synthesis in primary studies, when reporting the effects of pesticide use or exclusion, the pesticide names, application concentrations and timing should always be specified, together with information on fertilization and other potentially confounding variables. Critical consideration of sampling methods is also advisable, as pitfall trapping might not be appropriate if vegetation density differs among samples.

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Supplementary material

The following supplementary material is available as part of the online article (full text) from http://www.blackwell-synergy.com.

Table S1. Designs of the 30 studies reported in the systematic review.

Table S2. Variation in effects of crop-edge pesticide manipulation among different crops.

Table S3. Variation in effects of crop-edge pesticide manipulation among different widths of crop edge.

Figure S1. Variation in effects of crop-edge pesticide manipulation among different arthropod species.