ENHANCING NATURAL PEST CONTROL AS AN ECOSYSTEM SERVICE

Evidence for the effects of selected actions

Wright, H.L., Ashpole, J.E., Dicks, L.V., Hutchison, J.

& Sutherland, W.J.

NERC Knowledge Exchange Programme on

Sustainable Food Production

NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF CAMBRIDGE

Enhancing Natural Pest Control as an Ecosystem Service
Evidence for the effects of selected actions
NERC Knowledge Exchange Programme on Sustainable Food Production

This document should be cited as **Wright, H.L., Ashpole, J.E., Dicks, L.V., Hutchison, J. & Sutherland, W.J. (2013) Enhancing Natural Pest Control as an Ecosystem Service: Evidence for the Effects of Selected Actions. University of Cambridge, Cambridge.**

Contents

Funding

This work was funded by the Natural Environment Research Council (NERC) Knowledge Exchange Programme on Sustainable Food Production (grant no. NE/K001191/1).

Advisory board

We thank the following people for advising on the scope and content of this synopsis:

Dr Bhagirath Chauhan, International Rice Research Institute, Philippines
Dr Michelle Fountain, East Malling Research, UK
Dr Kong Luen Heong, International Rice Research Institute, Philippines
Dr John Holland, Game & Wildlife Conservation Trust, UK
Mr Jerry Tallowin, Rothamsted Research, UK
Prof Teja Tscharntke, Georg-August University Göttingen, Germany
Prof Steve Wratten, Lincoln University, New Zealand

Collaborators

The systematic map for the natural pest control synopsis was developed in partnership with **Dr Barbara Livoreil** at Fondation pour la Recherche sur la Biodiversité (FRB), Paris, France, and **Dr Klaus Peter Zulka** at the University of Vienna, Austria. We thank **Dr Georgina Key** at Lancaster University for her comments and editing and **Mr Ashley Bennison** for his assistance.

About the authors

Dr Hugh L. Wright is a Research Associate in the Department of Zoology, University of Cambridge.

Joscelyne E. Ashpole is a Research Assistant in the Department of Zoology, University of Cambridge.

Dr Lynn V. Dicks is a Research Associate in the Department of Zoology, University of Cambridge.

James Hutchison is a Research Assistant in the Department of Zoology, University of Cambridge.

Prof William J. Sutherland is the Miriam Rothschild Professor of Conservation Biology at the Department of Zoology, University of Cambridge.

1. About this synopsis

What are synopses of evidence?

Synopses of evidence synthesize and disseminate scientific research findings for practical use, focusing on the effectiveness of actions that practitioners may take. Synopses have been widely applied in medical disciplines and, more recently, to support biodiversity conservation through the Conservation Evidence[1] project, which has already summarized evidence for amphibian, bee, bird and northern and western European farmland conservation. In 2012-2013 the NERC Knowledge Exchange Programme on Sustainable Food Production[2] developed three synopses to assess the effectiveness of actions for: improving the sustainability of Atlantic salmon and warm water prawn aquaculture; improving the condition of farmed soils; and enhancing the ecosystem service of natural pest control (the focus of this document).

The purpose of Conservation Evidence/NERC Knowledge Exchange synopses:

Synopses of evidence do:	Synopses of evidence **do not**:
• Bring together scientific evidence captured by rigorous trawls of scientific journals and wider literature searches on the effects of actions to produce food sustainably, improve ecosystem services and conserve biodiversity	• Include evidence on the basic science (e.g. crop biology, species ecology) of food production, farmed/wild species and habitats, and associated ecosystem services, or the threats to them.
• List all realistic actions for the subject in question (ecosystem services, food production systems, habitats or species groups), regardless of how much evidence for their effects is available	• Make any attempt to weigh or prioritize actions according to their importance or the size of their effects
• Describe each piece of evidence, including methods, as clearly as possible, allowing readers to assess the quality of evidence	• Weigh or numerically evaluate the evidence according to its quality
• Work in partnership with agricultural scientists, policymakers, farm advisors and other practitioners to develop the list of actions and ensure we have covered the most important literature	• Provide recommendations for farming methods and regimes, but instead provide scientific information to help with decision-making

[1] www.conservationevidence.com
[2] www.nercsustainablefood.com

Who is this synopsis for?

We hope you are someone who has to make decisions about how best to farm sustainably, support ecosystem services and/or conserve biodiversity. You might be a farmer, a land manager in the public or private sector, a farming advisor, a consultant, a conservationist, a policy maker, a campaigner or a researcher. The Conservation Evidence and NERC Knowledge Exchange synopses summarize scientific evidence relevant to your farming, conservation or broader land management objectives and the actions you could take to achieve them.

We do not aim to make your decisions for you, but to support your decision-making by telling you what evidence there is (or isn't) about the effects that your planned actions could have.

When decisions have to be made with particularly important consequences, we recommend carrying out a systematic review, as this is likely to be more comprehensive than the summary of evidence presented here. Guidance on how to carry out systematic reviews can be found from the Centre for Evidence-Based Conservation[3] at the University of Bangor.

The NERC Knowledge Exchange Project on Sustainable Food Production

The Programme aimed to enhance the use of science in efforts to make UK food production systems more environmentally sustainable. It ran from June 2012 to September 2013, and its main outputs are openly accessible.

The outputs from the Programme include:

- Synopses of evidence on aquaculture, maintaining soil, enhancing natural pest control and farming for wildlife, freely available and searchable on a web-based information hub[4] and in downloadable documents
- Papers presenting priority knowledge needs for sustainable agriculture (*1*) and aquaculture in the UK, as well as priority research questions for the UK food system[5] as a whole (*2*)
- Working partnerships built between research scientists and food businesses to address issues of sustainable production
- A published meta-analysis of trade-offs and synergies between different aspects of agricultural sustainability across land-management practices and environmental contexts (for further details contact Richard German[6])
- An online catalogue[7] of NERC research related to the UK food system

The programme adopted the Conservation Evidence methods of summarizing and disseminating evidence and the natural pest control synopsis was developed at the Conservation Evidence project's home in the Department of Zoology, University of Cambridge. The programme worked with Lancaster University, Plymouth Marine

[3] www.cebc.bangor.ac.uk
[4] www.nercsustainablefood.com
[5] www.foodsecurity.ac.uk/assets/pdfs/priority-research-questions-uk-food-system.pdf
[6] richard_german11@hotmail.com
[7] http://nercsustainablefood.com/site/page?view=contribution

Laboratory, University of Bangor, University of Leeds and the Global Food Security programme[8] to deliver the soils and aquaculture synopses and other outputs.

Scope of the natural pest control synopsis

The synopsis considers scientific evidence from across the world and for all conventional forms of terrestrial farming: arable, perennial and livestock or pasture systems. We use the term 'pests' to cover the complete range of economically damaging organisms in land-based farming, including vertebrate and invertebrate animals, plant weeds and pathogens (fungal, bacterial and viral).

We defined our range of crop types and livestock animals using the Food and Agricultural Organisation's (FAO) list of production commodities (*3*), supplemented by forage crops and pastures included in the United States Department of Agriculture (USDA) crop nutrient tool (*4*). For the purpose of this synopsis, 'farming' includes horticultural production of fruit and vegetables but flower, timber and garden plant cultivation are excluded.

Evidence is included irrespective of the date of study but, given the relatively contemporary subject area and our reliance on electronic library sources, the overwhelming majority of our evidence (99%) originates from after 1975.

Identifying actions for natural pest control

The complete list of 92 actions to enhance natural pest control (given in Annex 1) was developed from a list suggested by ecosystem service experts and presented in (*5*). These actions were refined and added to as we reviewed the literature on enhancing natural pest control. An international advisory board of seven experts (from academia, private-sector research and independent and charitable organisations) also commented on and added to the list.

Actions were included if they were interventions that farmers or land-managers would realistically be prepared to or could do. We included actions regardless of whether they had already been adopted or whether or not evidence for their effectiveness already existed.

The table below illustrates the major ecosystem processes which farmers and land-managers can feasibly use to manage pests, or those investigated by agricultural scientists to date. Over a third of the actions we have identified relate to maintaining or increasing the action of natural enemies. In some cases, and particularly for actions affecting soil microorganisms, the mechanisms of pest control may still be poorly known.

[8] www.foodsecurity.ac.uk

Mechanisms of natural pest control

Ecosystem service mechanisms	Example actions to enhance the services
• Predation, consumption, parasitism[1] or infection of pest vertebrates, invertebrates, weeds and pathogens by natural enemies (including beneficial soil fauna)	• Reducing agricultural pollution, providing habitats and resources, attractive chemicals, timing of farm practices, reducing tillage, green manures, soil amendments
• Pest and pathogen resistance in crops and animals (immune systems, systemic resistance)	• Selecting crop varieties and animal breeds, inducing systemic resistance using chemicals and biological agents
• Suppressive effects of crops and plants (plant chemistry)	• Repellent crops and plants (or their chemicals), push-pull cropping, crop rotation
• Attractive effects of crops and other plants (plant chemistry)	• Trap crops to influence pest movement, push-pull cropping
• Competitive effects of crops and other plants (natural competitors)	• Planting competitors, cover cropping, intercropping, mixed pasture, crop density
• Accessibility and spatial configuration of the crop or habitat (modifying pest movement and field climate)	• Crop density, cover cropping, mulching, intercropping, alley cropping, farm-scale crop diversity
• Soil conditions (prohibitive soil chemistry or structure)	• Mulching, green manures (biofumigation), fallowing, cover crops, crop rotation
• Ecosystem hydrology (impacts of water abundance or drought)	• Flooding, irrigation regimes
• Managing ecosystem disservices[2] (e.g. ants that protect insect pests)	• Restricting ant movements, culling

[1] In this synopsis 'parasitism' refers to the action of both parasites and/or parasitoids: parasites benefit from other organisms (known as 'hosts') by living on or inside them but not killing them, parasitoids also live on or inside other organisms but their hosts ultimately die.

[2] Ecosystems also provide disservices (the most obvious being the presence of pests themselves) and we also consider actions that manage or limit the ecosystem services supporting pests.

To identify actions, clear decisions had to be made regarding what should be considered a 'natural' ecosystem service. This synopsis does not cover the direct release of natural enemies (or 'biocontrol agents') and beneficial organisms as we deemed this an unnatural extension of ecosystem services. This applies to importing native and non-native natural enemies and augmenting existing, native natural enemies. Some of the actions included may result in the indirect, passive or unintentional release of beneficial organisms, such as amending the soil with organic processing wastes which could contain various microorganisms. However, in these actions the introduction of organisms may be one of a number of potential pest-controlling mechanisms and it may help to stimulate responses by organisms already occurring in the farmed ecosystem.

The artificial use of insect communication chemicals (such as pheromones) to control pests directly (e.g. to lure pests into traps) is not covered, but we have included actions that use these chemicals to manipulate the natural enemies of pests. Using materials that originate from outside of the farmed ecosystem is also not included unless these are enhancing a mechanism of natural pest control within the farmed ecosystem. For example, spraying crop foliage with compost extracts (from a variety of outside sources) may induce crop plants' natural resistance to pests and pathogens and is included. Amending the soil with pesticidal plant material is a direct method of natural pest control and is included if these plants were grown in the same farmed ecosystem as the pest(s), but not if the material was grown and processed elsewhere.

Where several actions are frequently combined together in practice (making it difficult to determine their separate effects) we have created broad actions such as 'convert to organic farming' and 'reduce pesticide, herbicide or fertilizer use generally (including integrated management methods)', in addition to the more specific actions that comprise them. However, where evidence is provided for individual actions we present this under the most specific action tested. Therefore a study on the effect of reducing herbicide use (as opposed to chemical use in general) would be included under 'reduce herbicide use', but would not appear under 'reduce pesticide, herbicide or fertilizer use generally (including integrated management methods)'.

How we reviewed the literature

To identify the scientific literature relevant to natural pest control we used two approaches: a literature search (querying databases with search terms) and a journal trawl (looking at every published article and manually selecting relevant papers, based on title or abstract). The literature search was undertaken by librarians at L'Institut National de la Recherche Agronomique (INRA), France (coordinated by our collaborators at FRB) and used search equations to draw references from electronic bibliographic databases. Search equations comprised strings of relevant terms in English, including a comprehensive list of pest groups (from INRA HYPPZ[9]), broad categories of natural enemies, types of interventions and their outcomes (e.g. 'increase', 'decrease', 'maintain' etc.). The search terms were chosen by an iterative process of searching and refining; see Annex 2 for the complete list of terms. The action terms used in this search focused on actions to maintain or restore natural (or semi-natural) habitat, meeting FRB's research needs but not providing such complete coverage of the interventions in our list (Annex 1) that are unrelated to habitat management, such as

[9] www7.inra.fr/hyppz/

'reduce pesticide use' or 'use crop rotation'. These actions were covered by the journal trawl approach described below.

Librarians searched two databases, CAB Abstracts and Web of Science, although the search equation was built primarily to suit the structure of CAB Abstracts and may have resulted in a less comprehensive search of Web of Science. These searches returned 33,852 studies (14,249 from CAB Abstracts and 19,603 from Web of Science) once duplicates were removed. Using benchmark lists of references derived from an initial Google search (83 references) and the journal trawl (see below, 39 references relevant to habitat management), FRB estimated that these searches obtained approximately 56% of the relevant literature. Additional searches using the term 'habitat natural pest control' (in English and in French) were conducted in Google to identify additional non-academic (or 'grey') literature in the top 150 hits. While this method did retrieve some key non-academic literature, there is undoubtedly much grey literature which we have not been able to capture.

All study titles were examined (by FRB, University of Cambridge and University of Vienna) and irrelevant references were excluded. Study abstracts for the remaining 10,824 references were then scanned to identify studies meeting two major criteria:

- there was an action that farmers or land-managers could do to enhance natural pest control on their land
- the effects of the action were monitored quantitatively.

These criteria excluded studies examining the effects of specific actions without actually doing them. For example, predictive modelling studies and those looking at species distributions in areas with supposed (but not precisely documented) longstanding management histories (correlative studies), were excluded. Such studies can suggest that an action is effective, but do not provide direct evidence of a causal relationship between the action and the observed biodiversity pattern.

For the journal trawl, the University of Cambridge searched three journals for studies testing relevant actions: *Agriculture, Ecosystems & Environment, Biological Control* and *Journal of Applied Ecology*. Study titles and abstracts were scanned from volume one through to the latest mid-2012 volumes, applying the criteria and returning 416 studies. The trawl identified studies relevant to all the pest control actions. We also included literature from a study-by-study trawl of the entire NERC Open Research Archive[10] and evidence already captured by the Conservation Evidence project, which trawls 34 general conservation and ecology journals continuously.

These literature review methods taken together returned a total of 3,947 studies monitoring the effects of interventions in the list. Our search methods mostly picked out English language papers or studies with abstracts written in English. Our database of references is therefore only a sample of the global literature, but is nonetheless a significant body of evidence. All the studies were assigned to actions (Annex 1). Those from the FRB/INRA search are being developed into a systematic map of natural pest control literature.

[10] http://nora.nerc.ac.uk/

Selecting actions for this synopsis

The great volume of relevant studies and the short timescale of the Knowledge Exchange Programme precluded us from summarizing all of the literature, therefore this synopsis presents the evidence from 176 studies covering 22 selected actions. To prioritize the actions we asked stakeholders from the food production industry, agricultural policy and academia to select their top 10 actions. A prioritisation exercise (using a modification of the Delphi process) was repeated four times with different groups of eight experts, during a workshop in Paris (in collaboration with FRB) in mid-January 2013. Participants came from several western European countries and were asked to vote on their personal top 10 actions and then agree the group's final top 10 by consensus. The priorities identified were encouragingly consistent between the four groups and are marked in Annex 1.

Five priority actions (each with fewer than 100 studies) are included in the synopsis, balancing the expert's priorities with this project's time constraints. The 17 other actions were chosen to represent all farming systems and the variety of different types of intervention in the complete list of actions. 'Use crop rotation' was a priority action with a very large literature and therefore for the purpose of this synopsis we consider the evidence for potato farming systems only. We also narrowed down the literature for 'Convert to organic farming' to include only experimental studies and not comparisons of existing farming systems.

How the evidence is summarized

Actions to enhance natural pest control are primarily presented by farming system. 'All farming' includes actions relevant to a range of terrestrial farming systems. Actions in more specific farming systems (arable, perennial and livestock/pasture farming) may have relevance to other farming systems but have not been tested in those other environments to date. We also include a section on the theme 'reducing agricultural pollution' which applies to all farming systems.

Each action section begins with a series of key messages and these group studies according to their results to provide a succinct summary of the overall evidence. Key messages compile the results in the following consistent order: parasitism and natural enemy numbers, pest abundance, crop damage, yield, economic benefits and cost. Elements that have not been researched are not presented. For example, several interventions have no evidence on costs or profits.

Studies are then individually summarized in chronological order, so the most recent evidence is presented at the end. The key results from each study are included with a brief explanation of methods (where space permits). For detailed information on methods we encourage you to access the original paper. Background paragraphs provide further information on the aims of the action, the likely mechanisms that deliver enhanced natural pest control or the methods used in the studies.

Studies that were published in more than one place are summarized only once, choosing the publication with the most stringent peer-review process (e.g. choosing academic journals over bulletins) or the most recent publication date. Studies using the same experimental set-up to test the same action are all summarized individually if there are (at least partially) different results elements presented. We indicate where studies overlap in the summary paragraphs.

Many studies investigated several actions at once. When the effects of different interventions can be separated the results are summarized separately under the relevant actions. However, often the effects of multiple actions cannot be separated and, when this is the case, the study is included for each relevant action and we highlight in the text that several actions were used.

Some of the literature was inaccessible to us, either because a full text version of the paper could not be obtained or because we lacked the translation services to handle papers other than those in English or French. For actions that do not contain all of the identified literature we include a statement in the background section (e.g. 'Here we present five of eight studies…') to inform you of how many papers we summarized versus how many were identified as relevant.

All the evidence in this synopsis can be searched and accessed freely at www.nercsustainablefood.com and www.conservationevidence.com, where links to related conservation actions and hyperlinks to full-text sources are provided.

Terminology used to describe evidence

Unlike systematic reviews of particular questions or actions, we do not quantitatively assess the evidence, or weight it according to quality. However, to allow you to interpret evidence, we clearly report the size and design of each trial. The table below defines the terms that we use.

The strongest evidence comes from randomized, replicated, controlled trials with paired-sites and before and after monitoring.

Terms for describing types of trial

Term	Meaning
Site comparison	A study that considers the effects of actions by comparing sites that have historically had different actions or levels of intervention.
Replicated	The action was repeated on more than one individual or site. In conservation and ecology, the number of replicates is much smaller than it would be for medical trials (when thousands of individuals are often tested). If the replicates are sites, pragmatism dictates that between five and ten replicates is a reasonable amount of replication, although more would be preferable. We provide the number of replicates wherever possible, and describe a replicated trial as 'small' if the number of replicates is small relative to similar studies of its kind.
Controlled	Individuals or sites treated with the action are compared with control individuals or sites not treated with the action.
Paired sites	Sites are considered in pairs, within which one was treated with the action and the other was not. Pairs of sites are selected with similar environmental conditions, such as soil type or surrounding landscape. This approach aims to reduce environmental variation and make it easier to detect a true effect of the action.
Randomized	The action was allocated randomly to individuals or sites. This means that the initial condition of those given the action is less likely to bias the outcome.
Before-and-after trial	Monitoring of effects was carried out before and after the action was imposed.
Review	A conventional review of literature. Generally, these have not used an agreed search protocol or quantitative assessments of the evidence.
Systematic review	A systematic review follows an agreed set of methods for identifying studies and usually for carrying out formal 'meta-analysis'. It will weight or evaluate studies according to the strength of evidence they offer, based on the size of each study and the rigour of its design. All environmental systematic reviews are available at: www.environmentalevidence.org/index.htm

Pesticides and herbicides

We use 'pesticides' to refer to insecticides, fungicides, molluscicides, rodenticides and nematicides but not herbicides, which are treated separately. The majority of pesticide-related studies focus on insecticides. This synopsis contains literature on all pesticides (including old studies on chemicals now banned in some countries) so we strongly recommend that you refer to the latest health and environmental requirements applicable to your area before undertaking the actions described. Readers should also be aware that chemicals may have beneficial or detrimental effects to crops and other organisms and we do not attempt to assess all of these impacts here.

Taxonomy

In general we employ the species names (common or binomial) used in the original paper and do not update taxonomy (or attempt to employ a universal common name). In a few cases we have updated taxonomy where the older binomial latin name is now clearly obsolete (e.g. corn earworm as *Helicoverpa zea* not *Heliothis zea*). Common and binomial names are both given the first time a species is mentioned in each summary paragraph.

Significant results

Throughout the synopsis we have quoted results from studies. These results reflect statistical tests presented in the paper, unless we state that studies 'report' a finding or that the effect was only slight. If statistical tests were not performed we typically report the results (e.g. 'There were 10 ladybirds in treatment A compared to 6 ladybirds in treatment B") without describing the difference between treatments (i.e. avoiding the terms 'higher', 'lower', 'greater', 'smaller' etc.).

(1) Dicks L., Bardgett R., Bell J., Benton T., Booth A., Bouwman J.*, et al.* (2013) What do we need to know to enhance the environmental sustainability of agricultural production? A prioritisation of knowledge needs for the UK food system. *Sustainability*, 5, 3095-3115.
(2) Ingram J.S.I., Wright H.L., Foster L., Aldred T., Barling D., Benton T.G.*, et al.* (in press) Priority research questions for the UK food system. *Food Security*, 5, 617-636.
(3) FAO. *FAOSTAT production domain commodities*. 2012 [cited 18/10/2012]; Available from: http://faostat.fao.org/site/384/default.aspx
(4) USDA. *Crop nutrient tool*. 2012 [cited 18/10/2012]; Available from: http://plants.usda.gov/npk/main
(5) Sutherland W.J., Gardner T., Bogich T.L., Bradbury R.B., Clothier B., Jonsson M.*, et al.* (in press) Solution scanning as a key policy tool: identifying management interventions to help maintain and enhance regulating ecosystem services. *Ecology and Society*,

2. Reducing agricultural pollution

2.1. Use pesticides only when pests or crop damage reach threshold levels

- **Natural enemies:** One[6] randomized, replicated, controlled study from Finland found that threshold-based spraying regimes increased numbers of natural enemies in two of three years but effects lasted for as little as three weeks.
- **Pests and disease:** Two[8,14] of four studies from France, Malaysia and the USA reported that pests were satisfactorily controlled. One randomized, replicated, controlled study[4] found pest numbers were similar under threshold-based and conventional spraying regimes and one study[5] reported that pest control was inadequate. A randomized, replicated, controlled study[12] found mixed effects on disease severity.
- **Crop damage:** Four[2,4,7,9] of five randomized, replicated, controlled studies from New Zealand, the Philippines and the USA found similar crop damage under threshold-based and conventional, preventative spraying regimes, but one study[3] found damage increased. Another study[13] found slightly less crop damage compared to unsprayed controls.
- **Yield:** Two[3,7] of four randomized, replicated, controlled studies found similar yields under threshold-based and conventional spraying regimes. Two studies[9,10,11,12] found mixed effects depending on site, year, pest stage/type or control treatment.
- **Profit:** Two[9] of three randomized, replicated, controlled studies found similar profits using threshold-based and conventional spraying regimes. One study[12] found effects varied between sites and years.
- **Costs:** Nine studies[2,3,4,5,6,7,8,9,14] found fewer pesticide applications were needed and three studies found[2,14] or predicted[8] lower production costs.
- **Crops studied** were barley[6], broccoli[8], cabbages[4,8], cauliflower[8], celery[7], cocoa[5], cotton[1], grape[14], peanut[12], potato[2], rice[9,10,11], tomato[3,13] and wheat[6].

Background

This involves switching from conventional, preventative pesticide applications (e.g. spraying every week, month or season) to a regime that monitors pest numbers or crop damage and applies pesticides only when these reach economically damaging levels (thresholds). Spraying regimes can be evaluated by assessing the number of occasions on which pests reached economically damaging levels after decisions to spray/not spray. Strategically timing insecticide sprays to coincide with periods of likely pest abundance or natural enemy susceptibility (anticipated in advance based on prior knowledge, experience or predictive models) is included in 'Alter the timing of insecticide use'. We use the term ‘pesticide’ to refer to insecticides (covering the majority of the evidence), fungicides and other chemicals to control non-plant organisms.

Here we present evidence from 14 of 29 studies testing this intervention.

A trial in Yavan, Tajikistan (*1*) reported that spraying regimes based on thresholds of economic damage by pests favoured the build-up of natural enemy

numbers in cotton *Gossypium* sp. crops. Up to 1,000 natural enemy insects were recorded per 100 plants in some instances, but more typical numbers were not presented. Farms using the threshold-based spraying regime applied pesticides to only 25-30% of cropped land, reportedly much less than on neighbouring farms. This conference abstract provided no details of experimental study design or the pesticide used.

A study in 1982-1983 in arable land on Long Island, New York, USA (*2*) found potato *Solanum tuberosum* damage was similar for growers who sprayed insecticide according to threshold-based recommendations and growers who did not. Growers using a threshold-based spraying regime used an average of 1.4-2.6 fewer sprays/year for controlling Colorado potato beetle *Leptinotarsa decemlineata* and 0.4 fewer sprays/year for controlling aphids (Aphidoidea), compared to growers not using the regime. The threshold-based regime saved US$70-130/ha on Colorado potato beetle control and US$12/ha on aphid control. The trial included 30 growers, who were classified as having followed the recommendations if their practice matched recommendations 60% of the time. This included spraying within 72 hours of a recommendation to spray, and not spraying when not recommended. Growers used a variety of recommended insecticides including aldicarb, disulfoton, phosmet, fenvalerate, parathion and methamidophos. Effects on natural enemies were not presented.

A randomized, replicated, controlled study in 1984-1985 in Florida, USA (*3*) found more armyworm *Spodoptera eridania* damage to tomato *Solanum lycopersicum* (affecting 1.7-3.4% of fruits) in plots sprayed when pests exceeded threshold levels compared to plots sprayed weekly (0.7-0.9%). Yield was similar between plots receiving the threshold-based spraying regime (464-541 marketable fruits/10 plants) and plots receiving weekly sprays (470-600 marketable fruits). The threshold-based spraying regime used seven applications of insecticide on average compared to 14 applications in the weekly regime. In the former, sprays were applied when monitoring found at least 0.7 leafminer *Liriomyza trifolii* larvae on tomato leaflets, or at least one armyworm on fruiting tomato plants (prior to fruiting the threshold was one armyworm/six plants). Cyromazine and methamidophos insecticides were used to manage leafminers and fenvalerate and permethrin were used to manage armyworms. Each spraying regime was replicated 12 times and tested under different planting densities (4.5, 9.0 and 18.0 feet between rows). Effects on natural enemies were not presented.

A randomized, replicated, controlled study in 1988-1989 in Oklahoma, USA (*4*) found similar numbers of cabbage loopers *Trichoplusia ni*, thrips *Frankliniella* spp. and aphids (Aphidoidea) in plots with a threshold-based spraying regime and plots with a conventional, weekly spraying regime, when averaged across the season. Damage to cabbages *Brassica oleracea* and cabbage yield were also similar in plots with threshold-based and conventional spraying regimes. Cabbages in the threshold-based regime were sprayed with Dipel 2X biological insecticide when moths and butterflies (Lepidoptera) averaged 0.5 larvae/plant in early to mid-growth stages and 0.3 larvae/plant in late growth stages. In the conventional regime plots received weekly sprays of *Bacillus thuringiensis* biological insecticide. Plots sprayed when pest thresholds were exceeded received 7-8 sprays compared to 11 sprays in the plots treated weekly. Each spraying regime was replicated 18 times. Insect pests were sampled on 5-10

plants/plot and one or two times/week. Figures and effects on natural enemies were not presented.

A trial in 1985-1988 in Sabah, Malaysia (*5*) found that lindane applications, made when monitoring confirmed that cocoa pod borers *Conopomorpha cramerella* were present, did not stop infestations from continuing to increase in January-June 1986. In 1987-1988, cocoa *Theobroma cacao* pod infestation was similar when insecticide applications were determined using either low or high pod infestation thresholds. At peak levels in 1987 and 1988, 74% and 21% of pods were infested in the low-threshold plot, respectively, versus 84% and 17% in the high-threshold plot. In January-June 1986 cocoa pod borer moths were monitored using pheromone traps and lindane was applied seven times in response to positive catches. In 1987-1988, thresholds were set using an index of pod infestation that quantified the percentage of infested pods at four severity levels. An experimental field was divided into two plots which were assigned different thresholds (index values of 5 and 30) for applying insecticide. Low-threshold plots received more cypermethrin applications than high-thresholds plots (22 vs seven applications in 1987, two vs zero applications in 1988). Pod infestation was assessed for each threshold treatment using 200-400 pods taken from 3-4 randomly selected heaps of harvested crop. Effects on natural enemies were not presented.

A randomized, replicated, controlled study in cereal fields in 1992-1994 in Finland (*6*) found more spiders (Araneae) in plots using a threshold-based spraying regime (peaking at 17-31 spiders/3 traps) compared to conventional plots sprayed annually (12-23 spiders) in 1992 and 1994. The effect lasted for three weeks in 1992 and at least six weeks in 1994, but overall spider numbers were similar between treatments in 1993. More money spiders (Linyphiidae) were found in plots in the threshold-based spraying regime (peaking at 10-20 spiders/3 traps) than conventional plots (9-12 spiders) in all years. Wolf spider (Lycosidae) numbers were only greater in the threshold-based than conventional plots in 1994. At the species level, only one of three species tested (the money spider *Erigone atra*) was affected by pesticide regime type. In the threshold-based regime, sprays were made when control thresholds were exceeded, resulting in one insecticide (pirimicarb) spray in 1992 and one herbicide spray in 1994. Insecticides (dimethoate and deltamethrin), fungicides (carboxin, imazalil and propiconazole), herbicides and growth regulators were applied annually in conventional plots. Barley *Hordeum vulgare* was grown in 1992-1993 and wheat *Triticum aestivum* in 1994. Spiders were captured using pitfall traps monitored weekly (8-10 times between sowing and harvest).

A randomized, replicated, controlled study in 1994-1997 in California, USA (*7*) found pest damage on celery *Apium graveolens* was similar in plots receiving threshold-based insecticide applications (5-39% plants damaged) and conventionally treated plots (5-33%) in 1995-1997. In 1994, damage was greater in threshold-based (38% plants) than conventional (20%) plots. Net profit was similar between threshold-based and conventional plots in 1994-1995 and 1997. In 1996 (an unprofitable year) net loss was smaller in threshold-based than conventional plots. A separate randomized, replicated, controlled commercial trial in 1997 found similar yield and net profit from plots with threshold-based applications (1,105-1,121 marketable cartons and US$8,000-8,330) and conventional plots (1,104 cartons and US$8,330). In the 1994-1997

test, threshold plots received selective insecticides (3-4 applications/year) when pest insect thresholds were exceeded. Conventional plots received broad spectrum insecticides to prevent pest build-up (8-9 applications/year). Treatments were replicated four times in plots of 16 celery rows, 20 m long. In 1997, conventional plots (receiving insecticide and fungicide) were compared with plots receiving either threshold-based insecticide application, threshold-based fungicide application, or both. Up to four fungicide and seven insecticide types were used per treatment. Treatments were replicated four times (0.4 ha plots). Effects on natural enemies were not presented.

A replicated study in 1998-2001 in Gisborne and Hawke's Bay, New Zealand (*8*) reported better control of pests by natural enemies when a threshold-based spraying regime was applied compared to conventional regimes. Insecticide use in vegetable *Brassica* spp. crops was reduced by 40-70% in the second year of the threshold-based spraying programme compared to conventional regimes. The threshold-based regime could potentially save NZ$125/ha when accounting for the cost of monitoring pests and assuming that spraying could be reduced by 3-4 applications/ha. Sprays (using a variety of insecticide types) were timed according to thresholds of diamondback moth *Plutella xylostella* and aphid (Aphidoidea) infestation, with selective insecticides used in rotation within each year. Details of experimental setup were not provided.

A 13-year randomized, replicated, controlled study in the Philippines (*9*) (the same study as (*10*) and (*11*)) found that spraying based on thresholds of pest abundance or damage typically resulted in less control of rice *Oryza sativa* leaf damage (averaging 31-34% control) than a full protection regime (60%), and similar control to preventative (41%) and farmers' practice regimes (24%). Rice yields were lower in threshold-based spraying regimes (4.5-4.6 t/ha) than for full protection (5.0 t/ha), similar to preventative (4.8 t/ha) and farmers' practice (4.5 t/ha) regimes but greater than in untreated plots (4.4 t/ha). Average monetary return from threshold-based spraying ranged from a US$-23/ha loss to a US$48/ha gain, compared to US$-34/ha to US$24/ha with the preventative regime and US$-9/ha to US$28/ha with farmers' practice. Thresholds were studied at 4-9 farms/year in four sites totalling 68 rice crops overall. Plots receiving full protection were sprayed with insecticides weekly. Plots receiving the preventative regime received carbofuran granules and two insecticide (chlorpyrifos) sprays. Farmers' practice involved low insecticide doses and timing based on prevention or very low pest thresholds. Plots measured 100-200 m^2. Leaf damage was measured relative to 0% control in untreated plots. Effects on natural enemies were not presented.

A 13-year randomized, replicated, controlled study in the Philippines (*10*) (the same study as (*9*) and (*11*)) found that spraying based on thresholds of leaffolder (Crambidae and Pyralidae) abundance or damage typically resulted in greater rice *Oryza sativa* yields than unsprayed controls (averaging 41-263 kg/ha greater). Yields were improved with five out of eight different spraying thresholds tested during initial rice growth, and with six out of eight thresholds tested in the flowering and ripening stages. The most effective threshold was that of 10-15% leaffolder leaf damage, which enabled correct decisions to spray/not spray on 93-99% of occasions. Thresholds based on the numbers of leaffolder larvae or moths led to 91-100% and 62-96% correct decisions, respectively. Synthetic insecticides (endosulfan, monocrotophos, BPMC and

azinphos-ethyl) controlled 65-100% of leaffolder larvae but only 13-53% of leaf damage. Thresholds were studied at 4-9 farms/year in each of four sites across the Philippines, totalling 68 rice crops overall. Thresholds and unsprayed controls were tested in 100-200 m^2 plots. Decisions were considered correct if leaf damage reached 10-15% and yield loss exceeded 250 kg/ha (in additional control plots). Comparisons to a conventional spraying regime and effects on natural enemies were not presented.

A 13-year randomized, replicated, controlled study in the Philippines (*11*) (the same study as (*9*) and (*10*)) found greater rice *Oryza sativa* yield (by 130-299 kg/ha) when sprays were based on thresholds of stem borer *Scirpophaga* spp. egg abundance and rice plant damage compared with no treatment. Thresholds based on moth abundance resulted in similar yields to untreated controls (17-65 kg/ha difference). The most effective thresholds assessed deadhearts (percentage of leaves killed by stem borers) and enabled correct decisions to spray/not spray on 90-99% of occasions. The most effective threshold level depended on the stage of crop growth (5%, 25% and 10% deadhearts for initial, flowering and ripening stages, respectively). At best, insecticides (endosulfan, chlorpyrifos or chlorpyrifos and BMPC) controlled 36% of plant damage and at worst they increased damage by 5% (at three weeks after planting). Thresholds were studied at 4-9 farms/year in each of four sites, totalling 68 rice crops overall. Thresholds and unsprayed controls were tested in 100-200 m^2 plots. Decisions were considered correct if deadhearts reached 5-15% per 20 plant hills, and if yield loss exceeded 250 kg/ha (in additional control plots). Comparisons to a conventional spraying regime and effects on natural enemies were not presented.

A randomized, replicated, controlled study in 2002-2004 in Georgia, USA (*12*) found more severe stem rot *Sclerotium rolfsii* in sprayed plots treated when weather and soil temperature thresholds were met than in conventional plots treated regularly (10-22 vs 5-8 average disease rating), on two occasions. Stem rot severity was similar between plots on three other occasions. Leaf spot (Mycosphaerellaceae) severity showed inconsistent differences between threshold-based and conventional plots (1.3-4.3 vs 1.9-3.9 average disease ratings). Yields were similar in threshold-based and conventional plots on three occasions (3,290-4,750 vs 3,260-4,980 kg/ha), but lower in threshold-based than conventional plots on two occasions (4,200 vs 4,560 kg/ha and 3,040 vs 3,490 kg/ha). Monetary return was similar between threshold-based and conventional plots on three occasions (US$1,050-1,750/ha vs US$1,110-1,770/ha), but lower in threshold-based plots on one occasion (US$1,480 vs US$1,580). Fungicide regimes were tested in peanut *Arachis hypogea* crops for three years at two sites (up to six occasions in total). Rainfall thresholds were used to time fungicide sprays, and soil temperature thresholds were used to select between tebuconazole and chlorothalonil fungicides. Weather and soil temperature closely related to types and extents of fungal diseases. Effects on natural enemies were not presented.

A trial in 2000-2002 in Hawke's Bay, New Zealand (*13*) found that tomato *Solanum lycopersicum* damage did not exceed the commercially acceptable level of 5% at harvest on 16 of 17 occasions when decisions to spray were made using thresholds of cotton bollworm *Helicoverpa armigera* larvae abundance. On average, 0.8-5.5% of tomatoes were damaged in treated fields compared with

3.9-7.1% in unsprayed fields (where thresholds were also exceeded). The decision to not treat crops while maintaining < 5% damage was correct 10 out of 11 times. Treatment decisions were made for 22 fields which all met or exceeded a conventional threshold of one larvae/plant. However, in 16 fields and one half-field, spraying only took place if larvae numbers exceeded an adjustable threshold accounting for site-specific parasitism rates (see 'Incorporate parasitism rates when setting thresholds for insecticide use'). Thresholds varied from 1-8.3 larvae/plant. Insecticides included spinosad or *Bacillus thuringiensis* pesticidal bacteria. Fruit damage was assessed for 40 random plants/field. Three fields and one half-field were left unsprayed to assess crop damage without treatment, but the effects of spraying with and without a pest threshold approach were not compared. Effects on natural enemies were not presented.

A trial in 2008-2009 in Aquitaine, France (*14*) during flavescence dorée outbreaks reported that a threshold-based spraying regime controlled this disease (caused by *Candidatus* Phytoplasma vitis bacteria) in two grape *Vitis vinifera* vineyard landscapes, as the disease carrying pest (the American grapevine leafhopper *Scaphoideus titanus*) was very scarce after the first insecticidal spray. In one landscape, the threshold-based regime resulted in 4,299 sprayings compared to an estimated 14,919 sprayings had a conventional approach been taken. Spraying frequency was reduced by 54-72% across the two landscapes, and spraying costs fell by €19-29/ha. Compared to the conventional approach of three insecticide applications, the threshold-based regime comprised one application, followed by a second spray if leafhopper abundance exceeded 3 adults/trap. One yellow delta trap was set up per 30 ha (costing approximately €3/ha) and checked weekly. The threshold-based regime used circular buffers (with a 2 km radius) to define spraying areas around infected sites whereas, traditionally, entire districts were sprayed under the conventional regime. The threshold-based spraying regime was applied in two landscapes, and compared with theoretical estimates for insecticide use under the conventional regime. Effects on natural enemies were not presented and the insecticide type was not specified.

(1) Umarov S. & Tajibayev M. (1983) Pest management permits pesticide use to be reduced. *Proceedings of the 10th International Congress of Plant Protection: Plant Protection for Human Welfare, 20-25 November, 1983*. Brighton, UK, Vol 1, pp 1B-R35.

(2) Leach S.S., Fry W.E., Jones R.T., Loria R., Storch R.H., Sweet R.D.*, et al.* (1986) *Integrated systems for managing potatoes in the Northeast.* Agricultural Experiment Station University of Maine Technical Bulletin 116.

(3) Stanley C.D., Schuster D.J. & Jones J.B. (1988) Plant-row-spacing effect on insect activity, bacterial spot severity, and yield for staked-tomato production in west Florida. *Proceedings, Soil and Crop Science Society of Florida*, 47, 212-214.

(4) Roberts B.W. & Cartwright B. (1991) Alternative soil and pest management practices for sustainable production of fresh-market cabbage. *Journal of Sustainable Agriculture*, 1, 21-35.

(5) Wood B.J., Fee C.G., Cheong S.S. & Foh C.C. (1992) Trials on control of the cocoa pod borer *Conopomorpha cramerella* (Snellen) in Sabah by regular complete harvesting. *Tropical Pest Management*, 38, 271-278.

(6) Huusela-Veistola E. (1998) Effects of perennial grass strips on spiders (Araneae) in cereal fields and impact on pesticide side-effects. *Journal of Applied Entomology*, 122, 575-583.

(7) Reitz S.R., Kund G.S., Carson W.G., Phillips P.A. & Trumble J.T. (1999) Economics of reducing insecticide use on celery through low-input pest management strategies. *Agriculture, Ecosystems & Environment*, 73, 185-197.

(8) Walker G.P., Cameron P.J. & Berry N.A. (2004) Implementing of an IPM programme for vegetable brassicas in New Zealand. *Proceedings of the Fourth International Workshop, 26-29 November 2001*. Melbourne, Australia, pp 365-370.

(9) Litsinger J.A., Bandong J.P., Canapi B.L., Dela Cruz C.G., Pantua P.C., Alviola A.L., *et al.* (2005) Evaluation of action thresholds for chronic rice insect pests in the Philippines. I. Less frequently occurring pests and overall assessment. *International Journal of Pest Management*, 51, 45-61.
(10) Litsinger J.A., Bandong J.P., Canapi B.L., dela Cruz C.G., Pantua P.C., Alviola A.L., *et al.* (2006) Evaluation of action thresholds for chronic rice insect pests in the Philippines. III. Leaffolders. *International Journal of Pest Management*, 52, 181-194.
(11) Litsinger J.A., Bandong J.P., Canapi B.L., dela Cruz C.G., Pantua P.C., Alviola A.L., *et al.* (2006) Evaluation of action thresholds for chronic rice insect pests in the Philippines. IV. Stemborers. *International Journal of Pest Management*, 52, 195-207.
(12) Nuti R.C., Faircloth W.H., Lamb M.C., Sorensen R.B., Davidson J.I. & Brenneman T.B. (2008) Disease management and variable planting patterns in peanut. *Peanut Science*, 35, 11-17.
(13) Walker G.P., Herman T.J.B., Kale A.J. & Wallace A.R. (2010) An adjustable action threshold using larval parasitism of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in IPM for processing tomatoes. *Biological Control*, 52, 30-36.
(14) van Helden M., Fulchin E., Verpy A., Gil F. & Garcia C. (2011) Adult monitoring improves control of the flavescence dorée leafhopper *Scaphoideus titanus* in Gironde (France) while using less pesticide! *IOBC/WPRS Bul*
letin, 67, 9-16.

2.2. Incorporate parasitism rates when setting thresholds for insecticide use

- **Pest damage:** One controlled study[1] from New Zealand found using parasitism rates to inform spraying decisions resulted in acceptable levels of crop damage from pests. Effects on natural enemy populations were not monitored.

- The **crop studied** was tomato[1].

Background

This involves monitoring parasitism rates of pests by natural enemies and adjusting thresholds for insecticide use accordingly. Conventional threshold-based insecticide use (such as in integrated management) monitors pest populations or crop damage to schedule insecticide applications, but may not consider the action of natural enemies. Parasitoids can reduce pest populations, but there may be a lag between pest population increase and parasitoid population increase. If pests are killed by insecticides during this lag period, parasitoids may also be killed, preventing the parasitoid population from increasing and limiting the ecosystem service they provide. Monitoring parasitism rates to decide whether or not and when to spray is intended to avoid this and reduce unnecessary use of insecticides.

A controlled study in 2000-2002 in Hawke's Bay, New Zealand (*1*) found that tomato *Solanum lycopersicum* damage from cotton bollworm *Helicoverpa armigera* larvae did not exceed the commercially acceptable level of 5% on 16 of 17 occasions when treatment decisions were based on parasitism-adjusted pest thresholds. Only 1.2-5.5% of tomatoes were damaged in 11 fields where decisions to not spray crops used thresholds accounting for parasitism (damage exceeded the acceptable 5% level in only one field), and 3.0-3.4% were damaged in two sprayed fields where conventional thresholds (using pest but not parasitism levels) were used. Tomato damage averaged 3.9-7.1% in three unsprayed fields where cotton bollworm numbers exceeded parasitism-adjusted threshold levels. Treatment decisions were made for 22 fields which met or

exceeded a conventional threshold of one cotton bollworm larvae/plant, suggesting spraying was necessary. However, in 16 fields and one half-field, crops were only sprayed if bollworm numbers exceeded thresholds adjusted for site-specific parasitism rates (ranging 1-8.3 larvae/plant). Controls included two fields sprayed when only the conventional pest threshold was exceeded, and three fields and one half-field left unsprayed despite exceeding all thresholds. Insecticides included spinosad and *Bacillus thuringiensis* pesticidal bacteria. Fruit damage was assessed for 40 random plants/field.

(1) Walker G.P., Herman T.J.B., Kale A.J. & Wallace A.R. (2010) An adjustable action threshold using larval parasitism of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in IPM for processing tomatoes. *Biological Control*, 52, 30-36.

2.3. Alter the timing of insecticide use

- **Natural enemies**: One controlled study[1] from the UK reported more natural enemies when insecticides were sprayed earlier rather than later in the growing season.
- **Pests**: Two[1,2] of four studies from Mozambique, the UK and the USA found fewer pests or less disease damage when insecticides were applied early rather than late. Effects on a disease-carrying pest varied with insecticide type. Two studies[3,5] (including one randomized, replicated, controlled test) found no effect on pests or pest damage.
- **Yield**: Four studies[2,3,4,5] (including one randomized, replicated, controlled test) from Mozambique, the Philippines, the UK and the USA measured yields. Two studies[2,5] found mixed effects and one study[3] found no effect on yield when insecticides were applied early. One study[4] found higher yields when insecticides were applied at times of suspected crop susceptibility.
- **Profit and costs:** One controlled study[4] from the Philippines found higher profits and similar costs when insecticides were only applied at times of suspected crop susceptibility.
- **Crops studied** were aubergine[4], barley[2], maize[3,5], pear[1] stringbean[4].

Background

This involves applying insecticides at different dates in the growing season or at different times during the cropping cycle. Sprays can be reduced or avoided during periods of natural enemy vulnerability to reduce impacts on the ecosystem service they provide, although many studies test different dates simply to time spraying with periods of likely pest abundance or crop damage. Some of the evidence relates to chemicals now widely removed from use, and readers should bear in mind that using more selective insecticides may also allow greater flexibility in the timing of applications ('Use more selective pesticides' will be included in future synopses). Using historical information on pest population characteristics and crop susceptibility to time insecticides applications is included here. Informing spraying decisions by monitoring pests or crop damage within the present cropping season is included in 'Use pesticides only when pests or crop damage reach threshold levels'.

Here we present evidence from five of 13 studies testing this action.

A controlled study in 1978 in pear *Pyrus* sp. orchards in Kent, UK (*1*) found plots sprayed with permethrin in March had 2.9 flower bug (Anthocoridae) adults/beat, plots sprayed in July had 0.5 adults and plots sprayed in both months had 0.4 adults, when these natural predators were measured in August. Spraying in March reduced flower bug numbers from 0.05-0.10 adults/beat before spraying to 0.0 adults one month afterwards, while spraying in July reduced numbers from 0.8 to 0.5 adults. In late August, plots sprayed only in March had 9 pest pear psyllid *Cacopsylla pyricola* eggs/10 leaves, plots sprayed only in July had 55 eggs and plots sprayed in both months had 45 eggs. A 2 ha orchard was divided into four treatments receiving permethrin sprays (100 g a.i./ha) in March, July, March and July or no sprays. Predators were sampled by beating branches over a 0.3 m^2 funnel.

A randomized, replicated study in 1984-1985 in North Yorkshire, UK (*2*) found that barley yellow dwarf virus *Luteovirus* spp. created more patches of stunted barley *Hordeum vulgare* in plots sprayed on 13 November (averaging 11-16 patches/plot) than on 23 October (6-16 patches) or 31 October (7-14 patches). The area of stunted patches (ranging 1,124-4,087 cm^2) only differed between spraying dates in barley sown on 6 September rather than 18 or 27 September, and showed an increase with delayed spraying date. Effects of spray timing on English grain aphid *Sitobion avenae* (a carrier of the virus) depended on insecticide type. On all spraying dates, deltamethrin reduced aphids with no reinfestation later in the season. Demeton-S-methyl reduced aphids but limited reinfestation occurred (affecting < 3% of plants) in plots sprayed earliest (23 October). Pirimicarb also allowed reinfestation (affecting up to 6% of plants), particularly when applied early (23 October) or to plots sown on 6 September. The authors suggest that spraying early was effective for persistent insecticides, but spraying later (after aphid migration) was more effective for other insecticides. Yield (ranging 6.6-7.1 t/ha) was not consistently different between spraying dates. Three spraying dates were tested in plots of 2 x 24 m, replicated twelve times across three blocks testing sowing date effects.

A replicated study in 1987-1989 in Nebraska, USA (*3*) found similar root damage from western corn rootworm *Diabrotica virgifera* larvae in plots receiving insecticide before planting (average damage rating of 4.2) and plots receiving insecticide after planting (rating of 3.8). Maize *Zea mays* yields were also similar between plots treated before (10.5 t/ha) and after (10.9 t/ha) planting. Treatment prior to planting comprised chlorpyrifos granules applied at 34 g/1000 ft (304.8 m) of row. Treatment after planting was timed to correspond with corn rootworm egg hatch and early larval development and comprised chlorpyrifos emulsion at 1.12 kg/ha. Treatments were tested in 48.8 m^2 plots replicated four times. Root damage was scored from 1-6 with 1 being minor feeding damage and 6 equalling three or more root nodes destroyed/plant. Yields were assessed by hand harvesting two 20 ft (6.1 m) lengths of row in each plot.

A controlled study in November to March 1996-1997 and 1997-1998 in Nueva Ecija, Philippines (*4*) reported a lower impact of insecticides on ladybird and other insect natural enemies (Coccinellidae and Hymenoptera) following the strategic use of insecticides (during times of critical crop susceptibility to pests) compared to conventional practice. Net profit and yield of eggplant *Solanum melongena* crops were US$481 and 3.3 t/ha (respectively) following strategic

applications, compared with US$54 and 2.7 t/ha for conventional practices. Similar patterns were found for stringbean *Phaseolus vulgaris* profit and yield under strategically timed (US$718 and 6.9 t/ha) and conventional (US$576 and 6.7 t/ha) insecticide applications. The number of sprays was reduced from 13 for conventional practice to 10 for strategic application in aubergine, and from 13 to seven in stringbeans. The costs of production were US$875-1,072 for the strategic treatment and US$982-1,179 for the conventional practice. Insecticide applications in the strategic treatment were timed according to peaks in pest invertebrate population profiles monitored before the study in 1993-1996. No other details of experimental set-up or insecticide type were provided.

A randomized, replicated, controlled study in 1993-1994 in northern Mozambique (*5*) found similar numbers of stem borers (Noctuidae) in plots of maize *Zea mays* treated with insecticide at 0-40, 40-80 and 80-120 days after planting, and between 120 days and harvest (1.1, 0.1, 0.5 and 1.0 borers/plant, respectively). Plots treated at 0-40 days after planting had more stem borers than controls treated throughout the growing season (0.03 borers/plant), but plots treated at other times had similar pest numbers to continuously treated controls. There was no difference in the percentage of stems infested (15-39%) or plants lost (42-48%) to stem borers for any of the treatments and controls. Yield was greater in plots treated after 40-80 days (4.8 t/ha) than in plots treated at other specific times (2.5-3.9 t/ha), but was similar to continuously treated controls (4.5 t/ha). Plots treated after 0-40 days (2.5 t/ha) and between 120 days and harvest (2.6 t/ha) had lower yields than continuously treated controls. Cyhalothrin insecticide was applied weekly in each time period. Each treatment was replicated four times in plots of four maize rows, 5 m long. Stem borer larvae and pupae were counted on 10 plants/plot at 120 days after planting.

(1) Solomon M.G., Cranham J.E., Easterbrook M.A. & Fitzgerald J.D. (1989) Control of the pear psyllid, *Cacopsylla pyricola*, in South East England by predators and pesticides. *Crop Protection*, 8, 197-205.

(2) McGrath P.F. & Bale J.S. (1990) The effects of sowing date and choice of insecticide on cereal aphids and barley yellow dwarf virus epidemiology in northern England. *Annals of Applied Biology*, 117, 31-43.

(3) Peters L.L. & Lowry S.R. (1991) Western corn rootworm (Coleoptera: Chrysomelidae) larval control with chlorpyrifos applied at planting time versus a post-planting chemigation application to corn grown under two different tillage systems. *Journal of the Kansas Entomological Society*, 64, 451-454.

(4) Aganon T.M., Patricio M.G., Calderon J.I., Soriano J.S. & Sison M.L.J. (1997) Development of a vegetable IPM program in a rice-based cropping system. *Kasetsart Journal: Natural Sciences*, 32, 32-36.

(5) Davies G. (1998) A study of the pest status and control of maize stem borers on the Niassa Plateau, Mozambique. *International Journal of Pest Management*, 44, 225-234.

2.4. Delay herbicide use

- **Natural enemies:** Two[1,3,4] randomized, replicated, controlled trials from Australia and Denmark found more natural enemies when herbicide treatments were delayed. One[1] of the studies found some but not all natural enemy groups benefited and fewer groups benefitted early in the season.

- **Weeds:** One[1,4] randomized, replicated, controlled study found more weeds when herbicide treatments were delayed.
- **Insect pests and damage:** One[1] of two randomized, replicated, controlled studies from Canada and Denmark found more insect pests, but only for some pest groups, and one study[2] found fewer pests in one of two experiments and for one of two crop varieties. One study[2] found lower crop damage in some but not all varieties and study years.
- **Yield:** One randomized, replicated, controlled study[2] found lower yields.
- **Crops studied** were beet[1,4] and oilseed[2].

Background

Delaying herbicide application dates within a growing season may improve natural pest control as this encourages weeds to grow early in the season, providing habitat and resources to help natural enemy populations develop. These weeds may also divert generalist pests (those with broad habitat or resource requirements) that would otherwise reach the crop.

A randomized, replicated, controlled study in 2001 on Mors, Denmark (*1*) found more ladybird (Coccinellidae) and sawfly larvae (Symphyta) in mid-July in plots receiving late applications of herbicide (averaging 1.80 and larvae/0.9 m^2, respectively) at recommended (0.30 and 0.2 larvae) or early (0.05 and 0.05 larvae) spraying dates. More rove beetles (Staphylinidae), adult ground beetles (Carabidae) and money spiders (Linyphiidae) also occurred when plots were sprayed late (42 rove beetles, 6 ground beetles and 33 money spiders/0.9 m^2) rather than at recommended (19, 3 and 28, respectively) or early dates (18, 3 and 22). Rove beetles and money spiders showed similar patterns in mid-June. Groups that did not show an effect were not presented. Some pest groups such as planthoppers (Delphacidae) and leaf beetles (Chrysomelidae) were also more numerous in plots sprayed late. Plots treated later had more weeds (0.2-52.3 weeds/m^2) than plots treated at recommended or early dates (0.6-18.8 and 0.1-5.7 weeds, respectively). Beet *Beta vulgaris* yields were similar between treatments (870-970 t root/ha). Glyphosate was sprayed in three timing treatments: early application (25 May and again 27 June), recommended application (14 June and 5 July) and late application (27 June and 16 July).

Four randomized, replicated experiments in 1999-2001 in Alberta, Canada (*2*) found root maggot *Delia* spp. damage was generally lower in canola *Brassica napus* sprayed with herbicide at late rather than early crop growth stages. Two experiments found lower root damage in plots sprayed at six-leaf (damage rating of 2.5) rather than four-leaf (2.3 rating) and two-leaf (2.2 rating) stages in one of two canola cultivars, when averaged across sites, years and other treatments. Another experiment found this effect for two out of three cultivars and a fourth experiment found plots sprayed at the six-leaf stage had lowest damage in 1999 and 2001 (ratings of 2.7-3.2, 3.1-3.4 and 3.0-3.4 in six-, four- and two-leaf stages, respectively) but no effect in 2000. One experiment found less root maggot eggs in plots treated at the six-leaf (0.8 eggs/plant) rather than four- (1.4 eggs) and two-leaf (1.6 eggs) stages for one of two cultivars, but another experiment found only slight differences. Canola seed yields varied but were slightly lower in the six-leaf (392-3,265 kg/ha) than the two-leaf (672-3,458 kg/ha) stage treatments

in three experiments. Glufosinate was sprayed in three timing treatments replicated four times. Root damage was scored 1 to 5.

A randomized, replicated, controlled study in 2000 in Darwin, Australia (*3*) found more green twig-mining moths *Neurostrota gunniella* (natural enemies of the weed mimosa *Mimosa pigra*) survived when herbicide treatment to kill mimosa plants was delayed. Survival of green twig-mining moths was similar in herbicide-treated plots vs untreated controls when herbicides were applied 23 days (51-61 vs 48% of larvae survived to become adults) after moth egg laying, but survival was lower in the herbicide-treated plots when treated at 9 days (0-8% vs 49%) or 16 days (5-30% vs 80%) days since eggs were laid. Green twig-mining moth survival was similar for the three types of herbicide. Adult green twig-mining moths were released on 29 August to lay eggs on mimosa plants. Fluroxypyr, tebuthiuron and metsulfuron methyl herbicides were then applied at 9, 16 and 23 days after egg-laying. Treatments were tested in 5 x 5 m plots, each containing 20 mimosa plants grown in 30 cm-diameter pots. The number of larvae found before herbicides were applied was estimated from the number of leaflets mined by larvae. After herbicide treatment all emerging adult moths were collected using nets placed over the plants.

A randomized, replicated, controlled study in 2001 on Mors, Denmark (*4*) (the same study as (*1*)) found more arthropods (including insects and spiders) in July in plots receiving late herbicide applications (averaging approximately 525 arthropods/m^2) compared to plots receiving herbicide at recommended (290 arthropods) or early (230 arthropods) spraying dates. The diversity of arthropod groups and species in July was also higher in plots treated late (20 groups/0.9 m^2) rather than at recommended (16 groups) or early (12 groups) spraying dates. This study did not distinguish between pest and natural enemy arthropods and aphids (Aphidoidea), thrips (Thysanoptera), mites (Acari) and springtails (Collembola) were not included. More weeds occurred in mid-May to mid-August in plots sprayed late (2-89 g weed dry weight/m^2) than in plots sprayed at recommended (2-10 g dry weight) or early (2 g dry weight) dates. The experiment took place in 20 x 20 m plots of beet *Beta vulgaris*. Glyphosate herbicide (roundup ready) was sprayed in three timing treatments: early (25 May and again 27 June), recommended (14 June and 5 July) and late (27 June and 16 July) applications. Treatments were replicated four times. Arthropods were sampled with a Dietrick vacuum sampler.

(1) Strandberg B. & Bruus Pederson M. (2002) *Biodiversity in Glyphosate Tolerant Fodder Beet Fields: Timing of Herbicide Application.* Department of Terrestrial Ecology & National Environmental Research Institute Technical Report 410.

(2) Dosdall L.M., Clayton G.W., Harker K.N., O'Donovan J.T. & Stevenson F.C. (2003) Weed control and root maggots: making canola pest management strategies compatible. *Weed Science*, 51, 576-585.

(3) Paynter Q. (2003) Integrated weed management: effect of herbicide choice and timing of application on the survival of a biological control agent of the tropical wetland weed, *Mimosa pigra*. *Biological Control*, 26, 162-167.

(4) Strandberg B., Bruus Pederson M. & Elmegaard N. (2005) Weed and arthropod populations in conventional and genetically modified herbicide tolerant fodder beet fields. *Agriculture, Ecosystems & Environment*, 243-253.

2.5. Convert to organic farming

- **Parasitism and mortality** (caused by natural enemies)**:** One[7] of five studies (three replicated, controlled tests and two also randomized) from Europe, North America, Asia and Australasia found that organic farming increased parasitism or natural enemy-induced mortality of pests. Two studies[13,19] found mixed effects of organic farming and two[1,11] randomized, replicated, controlled studies found no effect.
- **Natural enemies:** Eight[2,5,6,7,13,14,15,18] of 12 studies (including six randomized, replicated, controlled tests) from Europe, North America Asia and Australasia found more natural enemies under organic farming, although seven[2,5,6,7,14,15,18] of these found effects varied over time or between natural enemy species or groups and/or crops or management practices. Three studies[9,16,17] (one randomized, replicated, controlled) found no or inconsistent effects on natural enemies and one study[12] found a negative effect.
- **Pests and diseases**: One[8] of eight studies (including five randomized, replicated, controlled tests) found that organic farming reduced pests or disease, but two studies[7,14] found more pests. Three studies[1,10,18] found mixed effects and two studies[4,9] found no effect.
- **Crop damage:** One[9] of seven studies (including five randomized, replicated, controlled tests) found less crop damage in organic fields but two studies[7,14] found more. One study[1] found a mixed response and three studies[3,8,11] found no or inconsistent effects.
- **Weed seed predation and weed abundance**: One[12] randomized, replicated, controlled study from the USA found mixed effects of organic farming on weed seed predation by natural enemies. Two[1,3,8] of three randomized, replicated, controlled studies from the USA found more weeds in organically farmed fields, but in one of these studies[1] this effect varied between crops and years. One study[4] found no effect.
- **Yield and profit:** Six randomized, replicated, controlled studies measured yields and found one positive effect[13], one negative effect[10] and one mixed effect[4], plus no or inconsistent effects in three studies[3,8,9]. One study[8] found net profit increased if produce received a premium, but otherwise profit decreased. Another study[4] found a negative or no effect on profit.
- **Crops studied** were apple[7,14], barley[2,15], beans[2,8,15], cabbage[3,18,19], carrot[19], gourd[13], maize[16,17], mixed vegetables[15], pea[2], pepper[9], safflower[8], soybean[12,16], tomato[1,4,6,8,10,11,17] and wheat[5,15].

Background

Organic farming is a set of actions that namely involves avoiding synthetic pesticides, herbicides and fertilizers (using organically derived chemicals and materials instead) and is often combined with different crop rotations and farming practices. Studies determining the individual effects of these actions are summarized separately for each action, but studies testing the whole suite of actions together are included here. Ground-dwelling invertebrates (such as ground beetles and spiders) are frequently surveyed using pitfall traps – small pots buried in the ground up to their rim and left empty or filled with liquid preservatives or water. Studies refer to 'activity densities' as pitfall trap measurements relate to both the abundance of beetles and their levels of activity on the ground (and therefore to the type of ground cover too).

This synopsis includes only those studies that experimentally tested organic farming, not those that compared existing organic systems. Experimental studies were typically conducted at laboratory, plot or field scales (17 of 19 studies presented here), but evidence for the effect of organic farming at the farm and landscapes scales (two studies here) is important and future synopses will also include comparative studies. Meta-analyses have found effects on pests and natural enemies can differ between field and farm scales (Bengtsson et *al.* 2005; Garratt *et al.* 2011).

Here we present evidence from 19 of 37 studies experimentally testing organic farming.

Bengtsson J., Ahnstr J.M. & Weibull A.-C. (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology*, 42, 261-269.

Garratt M.P.D., Wright D.J. & Leather S.R. (2011) The effects of farming system and fertilisers on pests and natural enemies: a synthesis of current research. *Agriculture, Ecosystems & Environment*, 141, 261-270.

A randomized, replicated, controlled study in 1989-1993 in northern California, USA (*1*) found 32% of tomato fruitworm *Helicoverpa zea* eggs were parasitized in organic plots compared to 25-37% in conventional plots of tomato *Solanum lycopersicum* in 1989. In organic plots, parasitism occurred on 0-9% of leaves with potato aphids *Macrosiphum euphorbiae* compared to 0-5% in conventional plots, across all years. Weeds were more widespread in organic than conventional plots for some years and crops, for example in maize *Zea mays* in 1991 (3.5% vs 0.5-1.8% ground cover). Plant-parasitic nematodes decreased in organic but increased in conventional plots in 1989-1992. Occurrence of disease and mobile pests was similar between treatments, and the authors suggest that pests may have migrated between the small plots. Organic tomato plots had more tomato fruitworm damage in 1989 and more stink bug (Pentatomoidea) damage in 1992 (1.5% and 11% of fruits damaged, respectively) than in conventional plots (0.0-0.5% and 6-7%), but damage was similar in other years. Organic plots were tilled to control weeds and conventional plots were treated with herbicides, insecticides, acaricides, fungicides and tilled. Treatments were replicated four times in 0.12 ha plots.

A randomized, replicated, controlled study in 1990-1991 in Alberta, Canada (*2*) found no difference in overall ground beetle (Carabidae) abundance between organic (averaging 194-200 beetles/plot) and conventionally farmed (145 beetles) plots. However, more ground beetles were found in organic (194-344 beetles/plot, across all species) compared to conventional (109-194 beetles) plots when a dominant non-native (and highly mobile) species was excluded from analysis. In 1991, four ground beetle species were more abundant in organic than conventional plots while two species showed the opposite trend. Species richness was also higher in organic (averaging 22.5-24 species) than conventional (16.5-21.5 species) plots in 1991. Organic and conventional regimes were examined in 10 x 25 m plots replicated eight times. Organic plots received mechanical and manual weed control and no synthetic fertilizers or herbicides. Conventional plots received synthetic fertilizer and/or herbicide. Each plot contained either barley *Hordeum vulgare*, faba bean *Vicia faba* or a barley-pea *Pisum sativum* intercrop. Beetles were sampled every two weeks from mid-June to mid-October 1990 and mid-April to mid-October 1991 using two pitfall traps in each plot.

A randomized, replicated, controlled study in 1993 in North Carolina, USA (*3*) found greater weed biomass in organic (1,178-1,265 kg/ha) than conventional (213-422 kg/ha) plots of cabbage *Brassica oleracea* after harvest (27th August). Damage by moth and butterfly caterpillars (Lepidoptera) was similar between treatments. Damage caused by alternaria leaf spot *Alternaria brassicae* was lower in organic (score of 2.7) than conventional plots (score of 4) under standard tillage conditions, but was similar between organic and conventional strip-tilled plots (scores of 3.2-4.4). Disease damage was scored from 0 (no disease) to 5 (severe damage). Cabbage weight and the percentage of marketable cabbage heads were similar between organic (0.5-0.8 kg/head and 90-95%, respectively) and conventional (0.6-0.9 kg and 93-95%) plots. Four treatments (organic/standard tillage, organic/strip tillage, conventional/standard tillage, conventional/strip tillage) were tested in plots of 8 x 14 m, replicated four times. Organic plots received soybean *Glycine max* meal fertilizer and mechanical weed control. Conventional plots received chemical fertilizers and herbicides. All plots received *Bacillus thuringiensis* insecticide applications. Weed biomass was sampled from 1 m^2 areas in the centre of plots. Twenty cabbage heads per treatment were examined for insect and disease damage at harvest.

A randomized, replicated, controlled study in 1992-1993 in Ohio, USA (*4*) found that organic tomato *Solanum lycopersicum* plots containing a mulch had similar broad-leaved weed and grass biomass (6.6-10.6 g dry weight/m^2 and 1.3-7.3 g, respectively) to conventional plots treated with herbicide (3.0-6.0 g and 0.7-1.3 g) at 12 weeks after planting. There were no differences in the frequency of insect pests and diseases between the management regimes. Tomato fruit yields were similar between organic (26 t/ha) and conventional (36 t/ha) plots at one site (Columbus), but lower in organic (35 t/ha) than conventional (66 t/ha) plots at a second site (Fremont). Economic return was similar between treatments (organic US$2,029 vs conventional US$2,068) in Columbus but lower in organic (US$2,743) than conventional (US$4,315) plots in Fremont. Organic plots had a cover crop mechanically killed and left as mulch before being cropped with tomato, and received organic fertilizer and mechanical weed control. Conventional plots were unmulched and received herbicides, insecticides, fungicides and synthetic fertilizer. Treatments were replicated four times and weeds and grasses were collected from four 0.5 m^2 areas within plots to calculate their biomass. Pests and diseases were scouted for weekly.

A randomized, replicated, controlled study in 1988-1991 in Therwil, Switzerland (*5*) reported 1.8-2.2 times more natural enemies in organic and biodynamic plots than in conventional plots of wheat *Triticum sp.*. More ground beetles (Carabidae) were found in organic and biodynamic plots (averaging 72-75 individuals) than conventional (46 individuals) plots in 1999, but only biodynamic plots had greater abundance (208 individuals) than conventional plots (89 individuals) in 1998 and no differences were found in 2000. Organic and biodynamic plots had more rove beetles (Staphylinidae, 42-58 individuals) than conventional plots (20-33 individuals) in 1998-1999, but there was again no difference in 2000. Spider (Araneae) abundance was similar between treatments in 1998 but was greater in organic and biodynamic (64-89 individuals) than conventional (28-45 individuals) plots in 1999-2000. Organic and biodynamic plots had 4-7.5 more ground beetle species (on average) than conventional plots. Treatments were tested in 10 x 20 m plots replicated four

times. Organic and biodynamic plots (farmed identically in this study) were fertilized with farmyard manure and weeds were controlled mechanically. Conventional plots received manure and mineral fertilizer and integrated plant protection. Natural enemies were sampled using 4-8 pitfall traps (of 10 cm diameter) per treatment.

A replicated, controlled study in February-November 1997 in Davis, California, USA (*6*) found that average ground beetle (Carabidae) abundance was 0-17 captures/week in organic plots compared with 0-7 captures in conventional plots of tomato *Solanum lycopersicum*. Abundance was higher in organic (6 captures/week) than conventional (2 captures) plots in June, but statistically similar at other times. The total number of ground beetles caught since February was higher in organic (averaging 33-46 captures) than conventional (18-22 captures) plots from June to November. Ground beetle species richness was higher in organic (averaging 2.3-3.5 species) than conventional (0.3-1.3 species) plots in June, September and November but not in other months. The organic system received no synthetic chemical insecticides, herbicides or fertilizers and included a legume cover crop prior to and after the tomato crop. Tomatoes were harvested in July. Each treatment was replicated four times in 0.12 ha plots. Beetles were sampled using two pitfall traps placed in the centre of each plot.

A replicated, controlled study in Hawke's Bay, New Zealand in 1995-1996 (*7*) found 24-58% of pest woolly apple aphid *Eriosoma lanigerum* colonies were parasitized by the wasp *Aphelinus mali* in organic orchards compared to 3-33% in conventional orchards. The wasp *Dolichogenidea tasmanica* parasitized 28% and 0% of leafrollers (Tortricidae) in organic and conventional apple *Malus domestica* orchards, respectively. The predatory mirid bug *Sejanus albisignata* appeared more abundant in organic than conventional orchards, but average numbers of predatory mites were similar (0.05-0.39 predatory mites per leaf overall). Woolly apple aphids were reportedly more frequent in organic (0-132 colonies/minute) than conventional orchards (0-37 colonies). In organic orchards, 59-95% of apples were undamaged compared with 90-99% from conventional orchards. Percentage fruit damage by leafrollers and woolly apple aphid in organic orchards was 1.8-4.5% and 0.002-39.6% respectively, compared with 0.1-1.2% and 0.03-11.5% in conventional orchards. Organic treatments included biological insecticide (*Bacillus thuringiensis*), organic fungicide, and disease control using minerals (e.g. slaked lime). Conventional orchards received 4-12 organophosphate insecticide applications and regular fungicides. Treatments were tested in 0.3-1.6 ha blocks at each of three sites.

A randomized, replicated, controlled study in 1989-1999 in northern California, USA (*8*) (same study as (*1*)) found that the density of weed seeds doubled (to 10,000 seeds/m^2) in organic plots relative to conventional plots over the 10-year study period. Fewer root-knot nematodes *Meloidogyne* spp. were found in organic than conventional plots in 1994, but the degree of galling on tomato *Solanum lycopersicum* roots was similar between treatments. Average crop yields were similar in organic versus conventional plots for tomato (67 vs 77 t/ha), safflower *Carthamus tinctorious* (2.4 vs 2.7 t/ha), maize *Zea mays* (10.5 vs 11.2 t/ha) and beans *Phaseolus vulgaris* (1.9 vs 1.7 t/ha). However, early in the experiment tomato and maize yields were lower in the organic than conventional plots. Organic plots were more profitable (cumulative net income US$6,875/ha by 1999) than conventional plots (US$4,438/ha) when premium prices were

applied, but the opposite was true without premiums for organic produce (a loss of US$-1,563/ha vs a gain of US$4,438/ha). Organic plots were tilled to control weeds and conventional plots were treated with herbicides, pesticides and tilled. Treatments were replicated four times in 0.12 ha plots.

A randomized, replicated, controlled study in 1998-2000 in Iowa, USA (*9*) found similar numbers of natural enemies in organic pepper *Capsicum annuum* plots (averaging 0.002-0.003 individuals/plant) and conventional plots (0.001-0.004 individuals) in 2000. Natural enemies included seven-spot ladybird *Coccinella septempunctata*, common green lacewing *Chrysoperla carnea* and spiders *Araneae*. In 1999, peppers had 0.25-0.58 natural enemies/plant in organic plots compared with 0.08-0.35 in conventional plots. Numbers of pest corn borer *Ostrinia nubilalis* larvae were similar between organic (0-0.04 individuals/plant) and conventional (0-0.02 individuals) plots in 1999-2000. Crop damage averaged 3-8.5 blemishes/fruit on organic peppers compared with 8.5-12.5 blemishes on conventional peppers in 2000. Pepper yields were generally similar between organic (7-38 peppers/plant) and conventional (6-47 peppers) plots in 1998-2000. Where significant yield differences were found these depended on the fertilizer regime and were not consistent between years. Organic plots received mechanical weed control and organic (or no) fertilizer. Conventional plots received herbicide and synthetic (or no) fertilizer. Organic management was tested in 16 or 24 plots (1998 and 1999-2000, respectively) and conventional management in 12 plots. Plots were 8 x 3 m and insects (natural enemies and pests) and yield were assessed for 10 plants/plot.

A randomized, replicated, controlled study in 2003-2004 in Fort Pierce, Florida, USA (*10*) found that the incidence of fusarium wilt (caused by *Fusarium oxysporum* fungus) was < 3% in organic plots of tomato *Solanum lycopersicum* compared to a range of 1-19% in conventional plots. Damage by root-knot nematodes *Meloidogyne* spp. was low for both types of management, with < 2% of root systems developing galls. Marketable tomato yields were reportedly lower in organic compared to conventional management plots. Organic and conventional regimes were applied for 3-4 years before the study crops were grown in 2003-2004. Organic plots received poultry manure and urban plant debris annually and had contained cover crops (sunn hemp *Crotalaria juncea* and Japanese millet *Echinochloa esculenta*) prior to the study. Conventional plots received soil fumigant and herbicides and had been cropped annually with tomato prior to the study. Each treatment was tested in six replicate 0.16 ha plots. Disease sampling methods were not described.

A randomized, replicated, controlled greenhouse trial on a tomato *Solanum lycopersicum* farm in Florida, USA (*11*) found root-knot nematode *Meloidogyne incognita* egg mortality and the number of eggs parasitized by fungi was similar between soils from organic (egg mortality 10-15 eggs, 0.5-2 eggs parasitized) and conventionally-managed treatments (mortality 12 eggs, 0-1 eggs parasitized). The severity of root galls on tomato plants was similar in soil from organic (0-0.92 on a scale of 0-10 where 10 is severe galling) and conventional plots (0.2-0.6). Cucumber *Cucumis sativus* plants planted after tomato also had similar root gall severity between both treatments. Tomatoes had been grown on the farm for 10 years. Treatments were set out in 0.16 ha plots and replicated six times. Organic plots were established in July 2000: treated with 22 t/ha chicken manure, 67 t/ha partially composted municipal plant waste and sown with two

cover crops: sunn hemp *Crotalaria juncea* in August and Japanese millet *Echinochloa crusgalli* in March. Conventional plots were treated with pesticides and herbicides. Soil samples were taken in each plot in July 2001, placed in 7.8 l plots in a greenhouse and planted with two tomato seedlings/pot. Nematode eggs were placed in each pot, one or six weeks after planting to assess mortality and fungal parasitism. Tomato roots were assessed for galling 42 days after transplanting. Cucumber plants were transplanted to the pots after the tomato plants were removed.

A randomized, replicated, controlled study in Michigan, USA (*12*) found that removal of weed seeds by ground beetles (Carabidae) was similar in organic (averaging 9-45% seeds predated/5 days) and conventional (13-40%) plots of soybean *Glycine max* from mid-August to early September 2000. In early August, 83-84% of weed seeds were predated in organic plots compared with 55-56% in conventional plots. Fewer ground beetles (of all types) were found on the soil surface in organic (57 captures/sampling date on average, 863 individuals in total) than in conventional plots (144 captures on average, 342 individuals in total), but seed predators in particular were similarly abundant between management regimes (averaging 6.2 captures in each). Organic plots received no external chemical input and conventional controls received applications of fertilizer and herbicide. Each regime was tested in 1 ha plots replicated six times. Ground beetles were sampled using five pitfall traps/plot. Seed predation was assessed by monitoring the removal of weed seeds placed artificially on the soil surface for 5 days. Seeds from common lambsquarters *Chenopodium album* or fall panicum *Panicum dichotomiflorum* were placed on a total of 120 pads for each management regime.

A randomized, replicated, controlled study in 1998-1999 in southern Sri Lanka (*13*) found more predatory weaver ants *Oecophylla smaragdina* in organic plots (averaging 4.4 ants/plant) than in conventional treated plots (0 ants) and similar numbers in organic and untreated (3.8 ants) plots. Mortality of pest fruit flies (Tephritidae) averaged 90-100% in organic plots compared to 80-100% in conventional plots at 14 days after flowering, and was higher in organic than untreated (30-50%) plots. Mortality of leaf beetles *Aulacaphora* spp. was similar in organic (71-81%) and conventional (71-82%) plots in three seasons, but lower in organic (80%) than conventional (100%) plots in the wet season, 1998. Leaf beetle mortality was higher in organic than untreated (21-42%) plots in all years and seasons. Yields of bitter gourd *Mormordica charantia* and snake gourd *Trichosanthes cucumerina* (combined) averaged 20-25 t/ha in organic plots compared with 15-20 t/ha in conventional and 5-10 t/ha in untreated plots. Organic, conventional and untreated regimes were replicated eight times across two sites using plots of 1.5 x 1.5 m. Organic plots received a insecticidal neem *Azadirachta indica* preparation. Conventional plots received carbaryl granules and sprays of fenthion insecticide.

A site comparison study in Drôme, France (*14*) reported more insect, spider and mite natural enemies in apple *Malus domestica* trees in an organic orchard (132 individuals in 2002, 181 in 2003) than in a conventional orchard (70 and 125 individuals). However, in 2001, 35 and 43 individuals were found in the organic and conventional orchards, respectively. In the grass beneath trees, natural enemies were typically more common in the organic than the conventional orchard. The combined number of pest rosy apple aphid *Dysaphis*

plantaginea, green apple aphid *Aphis pomi* and European red mite *Panonychus ulmi* in trees totalled 15,568 and 3,350 individuals in organic orchards (2002 and 2003), compared with 2,771 and 1,924 in the conventional orchard. In 2001, 94 and 237 pests were found in the organic and conventional orchards, respectively. Fruit damage from codling moth *Cydia pomonella* averaged 9.2% and 1.3% in the organic and conventional orchards, respectively. An organic orchard (0.25 ha) receiving granulosis virus and mineral fungicide applications was compared with a conventional orchard (0.2 ha) receiving insecticides, fungicides and herbicides. Treatments took place for two years before the study began. Invertebrates in trees were sampled by beating 50 branches per orchard.

A randomized, replicated, controlled study in 2005-2006 in Northumberland, UK (*15*) found that the response of natural enemies to organic farming varied between invertebrate families and crop types. In general, ground beetles (Carabidae) and spiders of the Lycosidae family were more abundant in organically fertilized (averaging 341-671 beetles and 11-37 spiders) than conventionally fertilized plots (285-429 beetles and 3-18 spiders), but not for all tested crop types. Rove beetles (Staphylinidae), money spiders (Linyphiidae) and parasitoid wasps (Braconidae) were typically less abundant in organic (61-125, 53-298 and 13-16 individuals, respectively) than conventionally fertilized plots (114-280, 85-413 and 18-23 individuals). Other natural enemies showed an inconsistent or no response to fertilization regime. Natural enemy abundance showed few or inconsistent differences between organic versus conventional crop protection (pest and weed control). Plots of 48 x 12 m were given organic (mechanical control and mineral applications) or conventional crop protection (synthetic herbicide and pesticide), then further divided into organic (compost or none) and conventional (inorganic) fertilization treatments. Each treatment was replicated 64 times with one of five crop types grown in each plot. Invertebrates were sampled using five pitfall traps (8.5 cm diameter) and three one-minute suction samples per plot.

A replicated study in Pennsylvania, USA (*16*) found no consistent trend in the occurrence of *Metarhizium anisopliae*, an insect-parasitoid fungus, during a three-year transition to organic farming. An experiment in 2003-2006 found more fungi in year one (2.3 samples with fungus, out of 3 samples/plot) than in year three (1.3-2 samples), but a second experiment in 2004-2007 found the opposite trend (1.8-2.1 samples in year one vs 2.3-2.4 samples in year three). Different crops were grown in each of the three years. The authors suggest variation between years and within seasons may explain the contradictory patterns in fungus numbers. Organic management practices were applied at one farm for a sequence of cover crops, soybean *Glycine max* and maize *Zea mays* (first, second and third years, respectively). Fungi presence was assessed using three soil samples at each of 24 randomly selected locations. Sampling took place on four dates between May and October each year.

A replicated, controlled study in 2005-2006 in Davis, California, USA (*17*) found similar numbers of predatory mites (Prostigmata and Mesostigmata) in organically farmed (7 mites/100 g soil) and conventionally farmed (5 mites) plots receiving standard tillage. Numbers of predatory mites were also similar between organic (12 mites/100 g soil) and conventional (8 mites) plots receiving reduced tillage. Organic plots with reduced or no tillage had more predatory mites (12-14 mites/100 g soil) than conventional plots with standard tillage (5

mites). Tomato *Solanum lycopersicum* and maize *Zea mays* were grown (in 2005 and 2006, respectively) in 0.4 ha plots. Organic management included compost fertilizer application and legume cover crops during winter. Conventional management included mineral fertilizer and bare fallow in winter. Subplots of standard and reduced tillage were tested under both management systems, and no-tillage was also tested in organic plots. Each treatment was replicated three times. Three soil samples were taken per plot at eight sampling dates in 2005-2006.

A controlled, replicated study in 2007-2009 in Årslev, Denmark (*18*) found 3-4 times more money spiders (Linyphiidae) in organic than conventional plots of white cabbage *Brassica oleracea* in July 2008. Other natural enemy numbers varied with the method of organic farming. Organic plots with bare soil around crops had 2-4 times more small (<8 mm length) predatory beetle (Coleoptera) activity in May and July 2008 than in other organic and conventional treatments (where numbers were similar). Ground beetles (Carabidae) were most frequent in green-manured organic plots (occurring in 50-70% of traps in May 2007 and 2008) but other organic treatments had similar or lower occurrence (5-30%) than the conventional control (25-30%). Cabbage root fly *Delia radicum* pupae were 2-3 times scarcer in organic than conventional plots, but numbers of fly eggs were similar between treatments. Cabbage was grown under four types of management: high-input organic, low-input organic with green manure incorporated before cropping (creating bare soil around crops), low-input organic with green manure strips conserved between crop rows, and a conventional control. Pitfall traps were used to sample natural enemies during the root fly egg-laying season.

A controlled, replicated study in 2006-2008 in Årslev, Denmark (*19*) (the same study as (*18*)) found fewer insect carcasses (including pests) infected by parasitoid fungi (Ascomycota: Hypocreales) in organically farmed plots with a green manure (1-11 carcasses/treatment) than in conventionally managed plots (14-24 carcasses), in September 2007 and 2008. Another organic treatment, alternating conserved strips of green manure between vegetable rows, had fewer infected insects (averaging 1.3 carcasses/plot) than conventional plots (7 carcasses) in September 2008. There were no differences between organic and conventional plots in other months (June to August) in 2007-2008. Only 17-28% of carcasses were of plant-eating pests, while 47-63% of carcasses were insect predators. White cabbage *Brassica oleracea* and carrot *Daucus carota* were grown in three replicate fields, each containing two organically managed treatments with undersowing (receiving different methods of green manuring) and a conventionally managed control. Treatments were applied to eight plots of 10 x 12.5 m in each field. Insect carcasses were sampled along nine 10 x 0.25 m transects per treatment per field, surveyed monthly from May to September in 2007 and 2008.

(1) Lanini W.T., Zalom F., Marois J. & Ferris H. (1994) Researchers find short-term insect problems, long-term weed problems. *California Agriculture*, 48, 27-33.

(2) Carcamo H.A., Niemala J.K. & Spence J.R. (1995) Farming and ground beetles - effects of agronomic practice on populations and community structure. *Canadian Entomologist*, 127, 123-140.

(3) Hoyt G.D. & Walgenbach J.F. (1995) Pest evaluation in sustainable cabbage production systems. *HortScience*, 30, 1046-1048.

(4) Creamer N.G., Bennett M.A., Stinner B.R. & Cardina J. (1996) A comparison of four processing tomato production systems differing in cover crop and chemical inputs. *Journal of the American Society for Horticultural Science*, 121, 559-568.
(5) Pfiffner L. & Niggli U. (1996) Effects of bio-dynamic, organic and conventional farming on ground beetles (Col. Carabidae) and other epigaeic arthropods in winter wheat. *Biological Agriculture & Horticulture*, 12, 353-364.
(6) Clark M.S. (1999) Ground beetle abundance and community composition in conventional and organic tomato systems of California's Central Valley. *Applied Soil Ecology*, 11, 199-206.
(7) Suckling D.M., Walker J.T.S. & Wearing C.H. (1999) Ecological impact of three pest management systems in New Zealand apple orchards. *Agriculture, Ecosystems & Environment*, 73, 129-140.
(8) Poudel D.D., Ferris H., Klonsky K., Horwath W.R., Scow K.M., van Bruggen A.H.C., *et al.* (2001) The sustainable agriculture farming system project in California's Sacramento Valley. *Outlook on Agriculture*, 30, 109-116.
(9) Delate K., Friedrich H. & Lawson V. (2003) Organic pepper production systems using compost and cover crops. *Biological Agriculture & Horticulture*, 21, 131-150.
(10) Chellemi D.O., Rosskopf E.N., Wu T., Graham J. & Martin K. (2005) Impact of land management practices on soilborne pests and productivity of tomato. *Proceedings of the 2005 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions, 31st October-3rd November, 2005*. San Diego, California, USA, p 48.
(11) Kokalis-Burelle N., Peries X. & Chellemi D.O. (2005) Effect of soils from six management systems on root-knot nematodes and plant growth in greenhouse assays. *Journal of Nematology*, 37, 467-472.
(12) Menalled F.D., Smith R.G., Dauer J.T. & Fox T.B. (2007) Impact of agricultural management on carabid communities and weed seed predation. *Agriculture, Ecosystems & Environment*, 118, 49-54.
(13) Rajapakse R. & Ratnasekera D. (2007) The management of the major insect pests *Bactocera cucurbitae* (Diptera: Tephritidae) and *Aulacaphora* spp. (Coleoptera: Scarabaeidae) in cucurbits in Southern Sri Lanka under three intensive systems: integrated, chemical and organic agriculture. *Acta Horticulturae*, 731, 303-308.
(14) Simon S., Defrance H. & Sauphanor B. (2007) Effect of codling moth management on orchard arthropods. *Agriculture, Ecosystems & Environment*, 122, 340-348.
(15) Eyre M.D., Sanderson R.A., Shotton P.N. & Leifert C. (2009) Investigating the effects of crop type, fertility managemen and crop protection on the activity of beneficial invertebrates in an extensive farm management comparison trial. *Annals of Applied Biology*, 155, 267-276.
(16) Jabbour R. & Barbercheck M.E. (2009) Soil management effects on entomopathogenic fungi during the transition to organic agriculture in a feed grain rotation. *Biological Control*, 51, 435-443.
(17) Sanchez-Moreno S., Nicola N.L., Ferris H. & Zalom F.G. (2009) Effects of agricultural management on nematode-mite assemblages: soil food web indices as predictors of mite community composition. *Applied Soil Ecology*, 41, 107-117.
(18) Meyling N.V., Navntoft S. & Eilenberg J. (2010) Organic farming systems benefit biodiversity and natural pest regulation in white cabbage. *ICROFS News*, 4-5.
(19) Meyling N.V., Thorup-Kristensen K. & Eilenberg J. (2011) Below- and aboveground abundance and distribution of fungal entomopathogens in experimental conventional and organic cropping systems. *Biological Control*, 59, 180-186.

3. All farming systems

3.1. Use alley cropping

- **Parasitism, infection and predation:** Two[3,8] of four studies from Kenya and the USA (including three randomized, replicated, controlled trials) found that effects of alley cropping on parasitism varied between study sites, sampling dates, pest life stages or the width of crop alleys. Two studies[6,7] found no effect on parasitism. One study[8] found mixed effects on fungal infections in pests and one study[3] found lower egg predation.
- **Natural enemies:** One[4] randomized, replicated, controlled study from Kenya found more wasps and spiders but fewer ladybirds. Some natural enemy groups were affected by the types of trees used in hedges.
- **Pests and crop damage:** Two[2,4] of four replicated, controlled studies (two also randomized) from Kenya, the Philippines and the UK found more pests in alley cropped plots. One study[1] found fewer pests and one study[5] found effects varied with pest group and between years. One study[2] found more pest damage to crops but another study[5] found no effect.
- **Weeds:** One[5] randomized, replicated, controlled study from the Philippines found mixed effects on weeds, with more grasses in alley cropped than conventional fields under some soil conditions.
- **Yield:** One[8] controlled study from the USA found lower yield and one study[5] from the Philippines reported similar or lower yields.
- **Costs and profit:** One study[8] from the USA found lower costs but also lower profit in alley cropped plots.
- **Crops studied** were alfalfa[8], barley[1,2], cowpea[7], maize[3,4,6,7], pea[2], rice[5] and wheat[1,2].

Background

This agroforestry intervention grows crops between hedgerows or tree lines planted at regular intervals across crop fields or along slope contours. Hedges may be pruned and the foliage used as mulch or green manure on the adjacent crop alleys. The technique may control weeds and insect pests in a number of ways, for example by modifying the field's climate, disrupting pest movement and weed growth, increasing crop vigour, providing habitat for natural enemies and using the insecticidal properties of hedgerow foliage. Studies that plant/allow trees around the edges of fields are included in 'Plant new hedges'.

Here we present eight of 10 studies testing this action.

A paired, replicated, controlled trial in 1993 and 1995 in West Yorkshire, UK (*1*) found winter barley *Hordeum vulgare* and winter wheat *Triticum* sp. had lower grain aphid *Sitobion avenae* (pest) densities in alley cropped plots than in control plots without tree rows. In 1993, alley cropped wheat had fewer grain aphids (average 8-23 aphids/wheat ear) than controls (22-39 aphids) in three of four plots, and alley cropped barley had fewer aphids in all four plots. Alley cropped plots had a lower ratio of wingless to winged grain aphids than controls (2.5-6.8 wingless to 1 winged aphid in alley cropped plots; 2.0-4.9 wingless to 1 winged aphid in controls). Wind speed was lower in alley cropped plots than in

controls without trees. Alley cropped plots were 14 m wide containing a 10 m-wide crop area separated by 2 m-wide tree rows. Controls had only boundary hedges and no tree rows. Tree rows (established 1988) contained ash *Fraxinus excelsior*, cherry *Prunus* spp., sycamore *Acer pseudoplatanus* and walnut *Juglans regia*, planted in sets of five and spaced 4 m apart. Hazel *Corylus avellana* bushes were planted between the trees. There were four replicates. Aphids were sampled by suction sampling and direct counts.

A paired, replicated, controlled study in 1991-1994 in West Yorkshire, UK (*2*) found more slugs in alley-cropped plots (averaging 14.3-20.6 slugs/pitfall trap) than in controls without trees (0.2-10.4 slugs) in 1992-1994. More roundback slugs *Arion* spp. occurred in alley-cropped plots (0.2-8.3 slugs/refuge trap) than in controls (0.0-0.3 slugs) in 1994. An average of 1.7-8.8 grey field slugs *Derocerus reticulatum*/refuge trap occurred in alley-cropped plots compared to 2.0-4.0 in controls in 1994. Within alley cropped plots, 5-8 roundback slugs and 6-9 grey field slugs/refuge trap were found in tree rows compared with 0-3 and 2-9 in crop alleys, respectively. The proportion of plants damaged by slugs was higher, and the number of emerging pea *Pisum sativum* plants was lower, next to tree rows than elsewhere in crop alleys or in the controls. Four plots of alley-cropped arable crops (using a wheat *Triticum aestivum*-barley *Hordeum vulgare*-pea rotation) were compared with paired, conventionally cropped controls. Rows of trees (containing five tree species) were established in 1987 and spaced 14 m apart. In 1994, slugs were sampled using 16 refuge traps (40 x 40 cm squares of roofing felt) in two pairs of alley-cropped plots and controls.

A randomized, replicated, controlled trial in 1992-1995 at two sites in Kenya (*3*) found that alley cropping had mixed effects on parasitism and predation of the pest maize stem borer *Chilo partellus* in maize *Zea mays* plots. Egg predation was lower in alley cropped plots (approximately 24-31% eggs predated/plot) than controls without hedges (44%) over two cropping seasons, but egg parasitism was similar over three seasons. Larval and pupal parasitism was higher in alley cropped plots than controls (4-6.4% vs 3.1% parasitism/plot) at one site, but the second site showed the reverse (1.2-9.8% vs 17.5%). Stem borer larvae mortality was slightly higher in alley cropped plots (averaging approximately 18-24% larval mortality/plot) than controls (17.5%) at one site. Hedgerow spacing (width of alleys) had mixed effects. Green lacewing *Chrysopa* spp. (natural enemy) egg abundance was similar between treatments. White leadtree *Leucaena leucocephala* hedgerows were established in 1992 and were 1.5 m (two plots), 2.25 m (six plots) or 3 m (two plots) apart with one, two or three maize rows between hedges, respectively. One plot per site was maize-only. Hedges were cut before cropping and the cuttings were mulched. Plots were 18 x 12 m (five replicates) or 12 x 10 m (four replicates).

A randomized, replicated, controlled trial in 1995-1996 in Machakos, Kenya (*4*) found more wasps (Hymenoptera) (65 vs 45) and spiders (Araneae) (96 vs 71) but fewer ladybirds (Coccinellidae) (14 vs 23) in alley cropped plots compared to conventional plots. Alley cropped plots had fewer aphids (Aphidoidea) (520 vs 895 individuals). Maize *Zea mays* had lower aphid *Rhophalosiphum maidis* and stalk borer (maize stalk borer *Busseola fusca* and *Chilo* spp.) infestations in alley cropped than conventional plots (21% vs 32% and 17% vs 30% infestation, respectively). However, alley cropped beans *Phaseolus vulgaris* had higher beanfly *Ophiomyia* spp. infestation than

conventional beans (35% vs 25% plants infested). The proportion of aphid *Aphis fabae* infestations in beans was similar between plots (14% vs 13%). The type of hedge species affected the abundance of some but not all pest and natural enemies studied. Hedges in alley cropped plots were planted 8 m upslope of crops in 1993 (using nine tree species) and pruned to 0.5 m. Beans were grown in the short- and maize in the long-rain season. Alley cropping was replicated 36 times and conventional cropping four times in 10 x 10 m plots. See also 'Plant new hedges'.

A randomized, replicated, controlled trial in 1987-1988 at two sites in Mindinao, Philippines (*5*) found that the weight of grass and broadleaved weeds averaged 3.4-86.1 g/m^2 and 0.7-51.3 g/m^2, respectively, in alley cropped plots of rice *Oryza sativa* compared to 1.2-16.4 g/m^2 and 2.6-35.6 g/m^2 in conventional plots. Grass weight was greater in alley cropped plots than controls at a site with low soil fertility and high erosion. Alley cropped plots had 0.8-25.8 rice seedling maggot *Atherigona oryzae* eggs/m crop row while conventional plots had 0.8-13.6 eggs. White grubs (Scarabaeidae) appeared less abundant in alley cropped than conventional plots in 1987 (8.5-11.5 larvae/5 m crop row vs 29.8 larvae at one site, 0.3-0.6 vs 2.0 larvae at a second site) but numbers were similar between these treatments in 1988. Stem borer damage resulted in 1.7-9.5 deadhearts (dried central rice shoots)/m of row in alley cropped plots compared with 0.78-16.3 deadhearts in conventional plots. Rice stover and grain yields averaged 0.66-6.27 t/ha and 0.09-1.48 (respectively) in alley cropped plots compared with 2.41-3.17 t/ha and 0.23-1.15 in conventional plots. Rice was planted in alleys between gliricidia *Gliricidia sepium* and cassia *Cassia spectabilis* hedgerows. Hedgerows followed contour lines and were spaced 3-6 m apart. Twenty-four alley crop plots (across two 0.6 ha sites) were compared with two plots receiving conventional farmers' practice. Alley cropped plots (grouped in this summary) included mulch, green manure, mulch and green manure, or non-amended treatments.

A replicated, randomized, controlled trial in 1999-2000 in Mtwapa, Kenya (*6*) found no significant differences in the number of parasitized stem borer (Lepidoptera) eggs, egg predation rates, larval and pupal parasitism and mortality rates between alley cropped maize *Zea mays* plots (with hedgerows of leucaena *Leucaena leucocephala* and/or gliricidia *Gliricidia sepium* trees) and plots without hedgerows. Hedges were planted in 1999 in plots of 16 x 13 m with 3.2 m alleys between hedges. Treatments included two plots with leucaena hedges, one plot with gliricidia hedges, two plots with alternating hedges of leucaena and gliricidia and four controls without hedges. This experimental design was replicated four times. Leucaena and gliricidia were pruned to 0.3 m before cropping and pruned foliage was applied as mulch. Four rows of maize were planted in 1999 and 2000 between hedges. Ten maize plants with stem borer egg batches were marked and inspected three days later for parasitism. Healthy and partially eaten eggs were analysed to identify parasitoids. Each week, stalks of 10 maize plants/plot were dissected to locate stem borers, which were then raised in the laboratory and assessed for parasitoids and mortality.

A replicated, randomized, controlled trial in 1999-2000 in Mtwapa, Kenya (*7*) (same study as (*6*)) found the average mortality of spotted maize stem borer *Chilo partellus* was similar between alley cropped maize *Zea mays* plots (with hedgerows of leucaena *Leucaena leucocephala* and/or gliricidia *Gliricidia sepium*

trees) and control plots without hedgerows (91-97% vs 94% mortality of larvae). When maize was intercropped with cowpea V*igna unguiculata*, alley cropped and control plots had similar stem borer mortality (93.9% vs 95.7%). Parasitism was not the major cause of stem borer mortality. Hedges were planted in 1999 in plots of 16 x 13 m with 3.2 m alleys between hedges. Treatments included two plots with leucaena hedges, one plot with gliricidia hedges, two plots with alternating hedges of leucaena and gliricidia and four controls without hedges. Trees were cut and the foliage was applied as mulch. Four maize rows were planted between hedges (0.8 m between each row). Maize and cowpea were planted in alternating rows in intercropped plots. Treatments were replicated 4-8 times. Ten maize plants/plot were collected on each sampling date and stem borer eggs, larvae and pupae were examined in the laboratory for parasitoids.

A controlled trial in 2004-2005 in Montana, USA (*8*) found lower survival in pest alfalfa weevils *Hypera postica* from alley cropped plots than from a control without alleys on two of four sampling dates (19-58% vs 41-73% larvae survived). Survival was similar with wide (24.4 m-wide) and narrow (12.2 m) alleys. Weevil fungal infection rates were higher in alley-cropped than control plots on two of four dates and parasitism was higher in narrow alleys than in wide alley and control plots on two dates. Alfalfa *Medicago sativa* yields were lower in plots with wide and narrow alleys (6,431-6,771 and 4,102-5,106 kg/ha, respectively) than in the control (8,800-9,223 kg/ha). Estimated costs were US$254-293/acre for wide and US$250-282/acre for narrow alley crops, compared with US$290-302/acre in the control. Predicted profit was only US$7-26/acre for wide alley crops and losses of US$-82 to US$-60 for narrow alley crops, compared with US$88-150 gains for the control. Alfalfa was established in a 2.5 ha plot within a black walnut *Juglans nigra* plantation using two distances between tree rows. A 2.5 ha control was planted with alfalfa monoculture. Weevil larvae were collected and reared in a laboratory to assess survival, fungal infection and parasitism.

(1) Naeem M., Compton S.G., Incoll L.D., Wright C. & Corry D.T. (1997) Responses of aphids to a silvoarable agroforestry landscape. *Agroforestry Forum*, 8, 18-20.
(2) Griffiths J., Phillips D.S., Compton S.G., Wright C. & Incoll L.D. (1998) Responses of slug numbers and slug damage to crops in a silvoarable agroforestry landscape. *Journal of Applied Ecology*, 35, 252-260.
(3) Ogol C.K.P.O., Spence J.R. & Keddie A. (1998) Natural enemy abundance and activity in a maize-leucaena agroforestry system in Kenya. *Environmental Entomology*, 27, 1444-1451.
(4) Girma H., Rao M.R. & Sithanantham S. (2000) Insect pests and beneficial arthropod populations under different hedgerow intercropping systems in semiarid Kenya. *Agroforestry Systems*, 50, 279-292.
(5) MacLean R.H., Litsinger J.A., Moody K., Watson A.K. & Libetario E.M. (2003) Impact of *Gliricidia sepium* and *Cassia spectabilis* hedgerows on weeds and insect pests of upland rice. *Agriculture, Ecosystems & Environment*, 94, 275-288.
(6) Midega C.A.O., Ogol C.K.P.O. & Overholt W.A. (2004) Effect of agroecosystem diversity on natural enemies of maize stemborers in coastal Kenya. *International Journal of Tropical Insect Science*, 24, 280-286.
(7) Midega C.A.O., Ogol C.K.P.O. & Overholt W.A. (2005) Life tables, key factor analysis and density relations of natural populations of the spotted maize stemborer, *Chilo partellus* (Lepidoptera: Crambidae), under different cropping systems at the Kenyan coast. *International Journal of Tropical Insect Science*, 25, 86-95.
(8) Stamps W.T., McGraw R.L. & Godsey L. (2009) The ecology and economics of insect pest management in nut tree alley cropping systems in the Midwestern United States. *Agriculture, Ecosystems & Environment*, 131, 4-8.

3.2. Plant new hedges

- **Natural enemies:** One[4] randomized, replicated, controlled study from China compared plots with and without hedges and found no effect on spiders in crops. One[2] of two studies from France and China found more natural enemies in a hedge than in adjacent crops while one study[4] found this effect varied between crop types, hedge species and years. Two[1,2] randomized, replicated, controlled studies from France and Kenya found natural enemy abundance in hedges was affected by the type of hedge shrub/tree planted and one[2] also found this effect varied between natural enemy groups.
- **Pests:** One[3] randomized, replicated, controlled study from Kenya compared fallow plots with and without hedges and found effects varied between nematode (roundworm) groups.
- **Crops studied** were barley[1,2], beans[2,3], maize[2,3,4] and wheat[4].

Background

Hedges or windbreaks are lines of trees or shrubs grown along the margins of crop and pasture fields or along orchard and plantation boundaries. Growing trees in rows within fields is included under 'Use alley cropping'. Ground-dwelling invertebrates (such as ground beetles and spiders) are frequently surveyed using pitfall traps – small pots buried in the ground up to their rim and left empty or filled with liquid preservatives or water. Pitfall trap measurements relate to both the abundance of beetles and their levels of activity on the ground, therefore studies refer to 'activity densities'.

Here we present evidence from four of six studies.

A trial in 1996 in Ouarville, France (*1*) found higher numbers of a predatory ground beetle *Pterostichus cupreus* in a newly planted hedge (273 catches/trap) than 10 m and 110 m into the adjacent barley *Hordeum vulgare* crop (23 catches). Other ground beetle (Carabidae) species, including *Pterostiehus melanarius*, had similar numbers or were only slightly more numerous in the hedge than the crop. Ground beetle diversity in the crop declined with distance from the hedge. The hedge was planted in 1995 and comprised two 200 m sections of shrubs divided by a 100 m section of mixed fodder crops (oat *Avena sativa* and cabbage *Brassica oleracea*). It was separated from the adjacent barley crop by a 9 m-wide zone planted with oats and sorghum *Sorghum bicolor*. Ground beetles were sampled using pitfall traps in the hedge (15 traps) and at intervals between 10-110 m from the hedge in the adjacent crop (four traps at each of five distances). Traps were emptied every 2-4 weeks (April to mid-October 1996). Fenced pitfall traps (12 in the hedge and three 110 m into the crop) were used to estimate absolute densities and were emptied every day for eight days in June 1996.

A randomized, replicated, controlled trial in 1995-1996 in Machakos, Kenya (*2*) found the type of hedge species affected the abundance of some but not all natural enemies and pests in bean *Phaseolus vulgaris* or maize *Zea mays* plots. During the dry season, there were more wasps (Hymenoptera) near hedges of croton *Croton megalocarpus*, gliricidia *Gliricidia sepium*, mulberry *Morus alba*, siamea *Senna siamea* and spectabilis *Senna spectabilis* (averaging 19-25 wasps/trap) compared to other hedge species (10-15 wasps). Spiders (Araneae)

were more abundant near hedges of calliandra *Calliandra calothyrsus*, croton, grevillea *Grevillea robusta*, lantana *Lantana camara* and siamea than other hedge species. Hedge type did not affect ladybird (Coccinellidae) or aphid (Aphidoidea) abundance or levels of pest infestation in beans and maize. Hedges were planted 8 m upslope of 10 x 10 m plots in 1993 using nine tree/shrub species (as above, plus flemingia *Flemingia macrophylla*) and pruned to 0.5 m. Beans were grown in the short- and maize in the long-rain season. There were four replicates/hedge species. Two yellow pan traps and two pitfall traps were placed in each plot (one of each near the hedge, one of each 4 m away) and monitored every 10 days.

A replicated, randomized, controlled study in 1998-1999 on a farm in western Kenya (*3*) found two plant-parasitic nematode (Nematoda) genera were more numerous in plots with vs plots without hedges of calliandra *Calliandra calothyrsus* and Napier grass *Pennisetum purpureum* (averaging 1,827-3,460 vs 960-2,973 nematodes/l soil) during the cultivation period. Three nematode genera had similar numbers in plots with and without hedges (0-20 vs 7-33 nematodes/l soil) during the cultivation period. Prior to cultivation, fallow plots with calliandra hedges had fewer individuals of five nematode genera and more individuals of two genera compared to fallows without hedges, but numbers did not differ statistically between these treatments. There were four replicates of each treatment in 15 x 12 m plots. A year before sampling, hedges of one Napier grass and one calliandra row (50 cm apart) were planted on the upper and lower edges of the plots. Crotalaria *Crotalaria grahamiana* fallows were established in plots in June 1998 and cultivation began in May 1999, when the crotalaria fallow was cut and sown with maize *Zea mays* and beans *Phaseolus* sp.. Soil samples were taken every two months from September 1998 until September 1999.

A randomized, replicated, controlled study in 2005-2007 in Sichuan, China (*4*) found similar activity densities of ground-dwelling spiders (Araneae) in plots with hedges (averaging 123-212 captures/3 pitfall traps) and control plots without hedges (118-208 captures). Vetiver *Vetiveria zizanioides* hedges had higher spider densities than false indigo-bush *Amorpha fruticosa* hedges (57 vs 44 captures/3 traps) and alfalfa hedges had higher densities than sabaigrass hedges (140 vs 108 captures) in wheat fields in 2006-2007. Differences in spider densities between hedges and adjacent crops (within plots) varied between years, crops and hedge types. All hedges had higher spider densities than wheat *Triticum* sp. (averaging 26-52 vs 16-20 captures/3 traps) in 2005-2006 but only sabaigrass *Eulaliopsis binate* and alfalfa *Medicago sativa* hedges had higher densities (34-46 captures) than adjacent wheat (16-17 captures) in 2006-2007. Sabaigrass and alfalfa hedges had higher spider densities (35-46 captures) than maize *Zea mays* (21-23 captures) in 2006 but hedges had similar densities to maize in 2007. Vetiver hedges, false indigo-bush hedges and bare control strips were tested in one field and sabaigrass hedges, alfalfa hedges and control strips were tested in another. Fields were divided into 7 x 6.5 m plots with each treatment replicated three times.

(1) Fournier E. & Loreau M. (1999) Effects of newly planted hedges on ground-beetle diversity (Coleoptera, Carabidae) in an agricultural landscape. *Ecography*, 22, 87-97.

(2) Girma H., Rao M.R. & Sithanantham S. (2000) Insect pests and beneficial arthropod populations under different hedgerow intercropping systems in semiarid Kenya. *Agroforestry Systems*, 50, 279-292.

(3) Kandji S.T., Ogol C.K.P.O. & Albrecht A. (2002) Influence of some agroforestry practices on the temporal structures of nematodes in western Kenya. *European Journal of Soil Biology*, 38, 197-203.
(4) Wu Y.H., Cai Q.N., Lin C.W., Chen Y.B., Li Y.Y. & Cheng X. (2009) Responses of ground-dwelling spiders to four hedgerow species on sloped agricultural fields in Southwest China. *Progress in Natural Science*, 19, 337-346.

3.3. Leave part of the crop or pasture unharvested or uncut

- **Natural enemies:** We found eight studies from Australia[5], Germany[3], Hungary[6], New Zealand[2], Switzerland[8] and the USA[1,4,7] that tested leaving part of the crop or pasture unharvested or unmown. Three[1,4,5] (including one replicated, controlled trial) found an increase in abundance of predatory insects or spiders in the crop field or pasture that was partly uncut, while four[4,5,6,7], (including three replicated, controlled trials) found more predators in the unharvested or unmown area itself. Two studies[2,3] (one replicated and controlled) found that the ratio of predators to pests was higher in partially cut plots and one replicated, controlled study[7] found the same result in the uncut area. Two replicated, controlled studies[3,8] found differing effects between species or groups of natural enemies.
- **Predation and parasitism:** One replicated, controlled study from Australia[5] found an increase in predation and parasitism rates of pest eggs in unharvested strips.
- **Pests:** Two studies[2,5] (including one replicated, controlled study) found a decrease in pest numbers in partially cut plots, one of them[5] only for one species out of two. Two studies[1,4] (one replicated, the other controlled) found an increase in pest numbers in partially cut plots, and two studies[4,5] (including one replicated, controlled study) found more pests in uncut areas.
- **Crops studied** were alfalfa[1,2,4,5,6,7] and meadow pastures[3,8].

Background

This action involves harvesting or cutting part of a crop field or pasture, often by leaving uncut strips. In pasture, fodder or perennial crops, these strips may be harvested later in a rotation system. The uncut areas provide a refuge for predators from harvesting itself, as well as providing habitat once the rest of the field is cut. This maintains predator populations and enables them to recolonize the following crop.

Here we present evidence from eight of 12 studies testing this action.

A controlled study in 1972 of two 16.1 ha alfalfa *Medicago sativa* fields in California, USA (*1*) found that predator and pest numbers were higher in the field with uncut strips than the completely cut field. There were 18,044 individual predators and 16,138 pest (lygus bugs *Lygus* spp. and pea aphids *Acyrthosiphon pisum*) individuals in the field with uncut strips and 7,131 predators and 12,557 pests in the completely cut field. Predators included spiders (Araneae), damsel bugs *Nabis* spp., green lacewing *Chrysoperla* (*Chrysopa*) *carnea* and ladybirds (Coccinellidae). Lygus bugs moved from uncut strips into cut areas, but moved back to uncut strips when cutting occurred. Predatory species showed a similar pattern. Alfalfa hay protein content was slightly higher in the field with uncut

strips (18.1-20.7% protein) than the completely cut field (17.1-18.2%) but modified crude protein was slightly lower. One field had banks 1 m wide and 0.2 m high distributed every 15-25 m. At each mowing period, banks were cut alternately (one alfalfa strip left uncut at every alternate raised strip, the next bank cut). Cuttings were distributed either side of the strip. Invertebrates were sampled on uncut and cut strips and between strips (10 samples/location) using a D-vac suction sampler. The second field was cut completely, and sampled using the same method as in the field with cut strips. Sampling took place one week after strip-cutting began (after the second cut, 7th May) and continued bimonthly until mid-September.

A controlled trial from 1978-1980 at Pukekohe, New Zealand (*2*) found a higher ratio of predators to aphids *Acyrthosiphon* spp. in five out of seven periods in a plot where strips of alfalfa *Medicago sativa* were left uncut than in a fully cut plot. The plot with uncut strips had fewer aphid outbreaks (two aphid outbreaks in seven interharvest periods) than a fully cut plot (four aphid outbreaks). Peak aphid numbers on alfalfa stems were also higher in the fully cut plot (5.5-400.3 aphids/stem) than the plot with uncut strips (0.6-124.6 aphids/stem). Two 40 x 60 m plots were compared: one continuously-cut plot and one strip-cut plot. In the strip-cut plot, two 10 m-wide strips were cut when the continuously-cut plot was mown, the remaining two strips were cut when the previously cut strips were half-grown. Aphids were sampled by sweep netting (50 sweeps/plot) and counting aphids on 10 alfalfa stems at six points along one transect/plot.

A replicated, controlled study from 1982 to 1986 in a meadow in Germany (*3*) found a higher ratio of predatory invertebrates to plant-eating insects in an area consisting of unmown and mown strips (0.66-2.55 predators/prey individual) than in a completely mown area (0.69-2.23). There were more spider (Araneae) species and a faster increase in diversity in the strip-managed area (average 40 species, 21 new spp./year) than the completely mown area (25 spp., 12 new spp./year). There were also more ground beetle (Carabidae) and rove beetle (Staphylinidae) species in strip-managed plots than mown plots (strip-managed: 33 ground beetle spp., 26 rove beetle spp.; mown plots: 24 ground beetle spp., 14 rove beetle spp.). The 44 x 6 m meadow plot was divided into: two 10 x 6 m plots (one mown, one unmown), four 1 x 6 m unmown strips and four 5 x 6 m mown strips. Mown and unmown strips were alternated. Plots were mown approximately every two weeks (5 cm high) during the growing season, cuttings were not removed. Unmown strips were not cut April 1982-autumn 1986. Invertebrates were sampled with six pitfall traps in the two mown/unmown plots and three traps in each strip. Traps were emptied every 10-14 days from June-September in 1982 and 1984-1986. Traps were not set in 1983.

A replicated trial in 1990-1991 on alfalfa *Medicago sativa* strips in cotton *Gossypium hirsutum* fields (*4*) found that strips where each half was cut alternately every 14-17 days had more natural enemies (big-eyed bugs *Geocoris* spp., minute pirate bugs *Orius* spp. and damsel bugs *Nabis* spp.) than a completely cut alfalfa field (alternately-cut strips every 14 days: 50.8-184 individuals/1.9 m^2; alternately-cut strips every 17 days: 148.8-181.7; completely-cut field: 39.3-101.5). However, alternately cut strips also had more lygus bugs *Lygus hesperus* (pest) than completely cut alfalfa (alternately-cut strips every 14 days: 43-66.6 individuals/1.9 m^2; alternately-cut strips every 17 days: 38.6-103; completely-cut: 4.6-8). Uncut strips had high numbers of lygus

bugs and natural enemies (128.4-191.4 lygus bugs/1.9 m^2, 87.1-339.4 natural enemies). Alfalfa strips (91.4 x 4.1 m) within the cotton crop or adjacent to it were established November 1989. Eight and twelve strips were studied in 1990 and 1991 respectively. Strips were cut completely on 30 April 1990 and 28 May 1991. There were three cutting treatments in both years, starting two weeks after the first cut: uncut, cut alternately every 28 days (one 2.05 m half strip cut, the other half cut 14 days later) or one alfalfa field cut completely every 28 days. In 1991, a 35 day alternate cutting treatment was also used (half the strip cut every 17 days). There were four replicates. Cuttings were not removed. Arthropods were D-Vac suction sampled weekly from May to August.

A replicated, controlled trial in 1997-1998 in a 4 ha alfalfa *Medicago sativa* field with strip- and conventional-harvesting in New South Wales, Australia (*5*) found that predation and parasitism of *Helicoverpa* spp. (pest) eggs was higher in unharvested (36.7% eggs predated, 3.31% parasitized) than harvested strips (21.7% eggs predated, 0.85% parasitized). Total predator abundance (spiders (Araneae), red and blue beetles *Dicranolaius bellulus* and transverse ladybird *Coccinella transversalis*) was higher in the strip-harvested area (average 5.1-9.1 predators/0.4 m^2) than the conventionally-cut area (1.2-7.6), and higher in unharvested than harvested strips. *Helicoverpa* spp. was less abundant in the strip- than conventionally-harvested area (0.1-9.2 individuals/0.4 m^2 vs 0.7-27.6) but another pest, lucerne leaf roller *Merophyas divulsana* had similar numbers in both treatments (0.3-18.4 vs 0.1-19.0); both pests were more abundant in unharvested than harvested strips. There were eight 200 x 14 m strips, split lengthways; one half cut a week before normal harvesting (harvested strip), one half cut two weeks later (unharvested strip). Subsequently, strips were cut when 10% alfalfa was flowering. Strips were vacuum-sampled five times. *Helicoverpa* spp. eggs were placed in strips to assess predation and parasitism rates. The 112 x 158 m conventionally-harvested block was cut three times, with three vacuum samples.

A replicated, controlled study in 1995-1997 in an alfalfa *Medicago sativa* field in Hungary (*6*) found leaving unmown strips increased the number of spiders (Araneae) in the unmown strips but did not increase numbers in adjacent mown strips. Unmown strips had an average of 53% more spiders than control continuously-cut control alfalfa plots. Average spider diversity was similar in controls and mown strips in rotation with unmown strips (control: 1.8 Shannon diversity; mown strips: 1.75). Unmown strips had slightly higher diversity (2.15). One 1.6 ha field was divided into six 50 x 50 m plots. Three plots were strip-managed (each mowing session four 1 m-wide strips were left unmown in each plot, the following mowing session these unmown strips were cut and adjacent 1 m strips left unmown), three plots were cut completely. Alfalfa was sown mid-April 1995. Plots were mown three-four times each year (starting July 1995) when approximately 10% of the alfalfa was flowering. Spiders were sampled 64 times from July 1995-December 1997, using three pitfall traps in control plots, three traps in unmown strips and three traps in mown strips. Suction samples were also taken at the pitfall trap locations.

Two replicated controlled trials from 1998-2000 in twelve 7.5-17 ha alfalfa *Medicago sativa* fields at 3-4 sites in Iowa, USA (*7*) found that in more than 50% of whole fields surveyed there were more predatory insects (net-winged insects (Neuroptera), minute pirate bugs (Anthocoridae), and ladybirds (Coccinellidae))

captured by sweep-netting in 3 m-wide uncut strips than cut areas, 1-3 weeks after hay had been collected (numbers not given). Numbers from sticky traps were similar between treatments. The proportion of insect predators to prey was higher in uncut than cut alfalfa in one field in 1998 and four in 1999, 1-4 weeks after cuttings were collected (uncut strips: 0.28-8.65 predators/prey, cut alfalfa: 0.06-0.94). In the plot-scale trial, predator numbers were similar between treatments and sampling periods in 1999. In 2000, uncut strips attracted insect predators in sweep net samples in weeks 1, 3 and 4, however ladybirds caught in sticky traps were more abundant in controls in one plot in week 1. Potato leafhopper *Empoasca fabae* (pest) numbers were higher in 73% of uncut strips surveyed for 2-3 weeks after harvest in 1998 and 2000. In 1999, leafhopper numbers were generally not higher in uncut than cut strips.

A replicated, controlled study on nine fen meadows in northern Switzerland (*8*) found overall spider (Araneae) species richness and abundance were similar between fallow strips and mown strips (fallow: 22.2 species, 75 individuals/m^2; control: 19.8 species, 82 individuals/m^2). Four out of ten spider families were more abundant in rotational fallows than completely mown plots (orb weavers (Araneidae), sac spiders (Clubionidae), ground spiders (Gnaphosidae) and jumping spiders (Salticidae)), four families had similar abundances (dwarf sheet spiders (Hahniidae), wolf spiders (Lycosidae), tangle-web spiders (Theridiidae) and crab spiders (Thomisidae)) and two had lower abundances in fallow strips (money spiders (Linyphiidae) and long jawed spiders (Tetragnathidae)). Three meadows were chosen in each of three regions. Starting in autumn 2002, in each meadow one plot of three 35-50 x 10 m-wide strips was mown rotationally (each year one of the three strips was not mown), and all three strips in the control plot were mown every year. Plots were mown in September and litter removed. Spiders were sampled March-June 2005 in each meadow using six emergence traps in the unmown fallow strip in the rotational plot and six traps in one mown strip in the control plot.

(1) Summers C.G. (1976) Population fluctuations of selected arthropods in alfalfa: influence of two harvesting practices. *Environmental Entomology*, 5, 103-110.
(2) Cameron P.J., Allan D.J., Walker G.P. & Wightman J.A. (1983) Management experiments on aphids (*Acyrthosiphon* spp.) and beneficial insects in lucerne. *New Zealand Journal of Experimental Agriculture*, 11, 343-349.
(3) Nentwig W. (1988) Augmentation of beneficial arthropods by strip-management. 1. Succession of predacious arthropods and long-term change in the ratio of phytophagous and predacious arthropods in a meadow. *Oecologia*, 76, 597-606.
(4) Godfrey L.D. & Leigh T.F. (1994) Alfalfa harvest strategy effect on lygus bug (Hemiptera: Miridae) and insect predator population density: implications for use as trap crop in cotton. *Environmental Entomology*, 23, 1106-1118.
(5) Hossain Z., Gurr G.M. & Wratten S.D. (2001) Habitat manipulation in lucerne (*Medicago sativa* L.): strip harvesting to enhance biological control of insect pests. *International Journal of Pest Management*, 47, 81-88.
(6) Samu F. (2003) Can field-scale habitat diversification enhance the biocontrol potential of spiders? *Pest Management Science*, 59, 437-442.
(7) Weiser L.A., Obrycki J.J. & Giles K.L. (2003) Within-field manipulation of potato leafhopper (Homoptera: Cicadellidae) and insect predator populations using an uncut alfalfa strip. *Journal of Economic Entomology*, 96, 1184-1192.
(8) Schmidt M.H., Rocker S., Hanafi J. & Gigon A. (2008) Rotational fallows as overwintering habitat for grassland arthropods: the case of spiders in fen meadows. *Biodiversity and Conservation*, 17, 3003-3012.

3.4. Grow non-crop plants that produce chemicals that attract natural enemies

- **Natural enemies:** Four studies from China, Germany, India and Kenya tested the effects of growing plants that produce chemicals that attract natural enemies. Three[1,3,4] (including one replicated, randomized, controlled trail) found higher numbers of natural enemies in plots with plants that produce attractive chemicals, and one[3] also found that the plant used attracted natural enemies in lab studies. One[2] found no effect on parasitism but the plant used was found not to be attractive to natural enemies in lab studies.
- **Pests:** All four studies[1,2,3,4] found a decrease in either pest population or pest damage in plots with plants that produce chemicals that attract natural enemies.
- **Yield:** One replicated, randomized, controlled study[4] found an increase in crop yield in plots with plants that produce attractive chemicals.
- **Crops studied** were sorghum[2], safflower[4], orange[3] and lettuce[1].

Background

This action involves growing non-crop plants which produce volatile chemicals (quickly evaporating scents or odours) that attract natural enemies, thereby encouraging the enemies to the main crop. Non-crop plants could be grown in field margins or interspersed into the main crop. Lab studies demonstrating an attractive effect of a plant species or variety to a natural enemy are also included.

Here we present evidence from four of six studies testing this action.

A controlled study in summer 2000 in Bonn, Germany (*1*) found that the abundance of four natural predators was significantly higher in lettuce *Lactuca sativa* plots intercropped with attractant plants (3.0-3.2 larvae and 3.2-3.6 adults per lettuce plant) than in monoculture lettuce plots (1.5 larvae and 1.7 adults). Egg and pupae abundance of the three ladybird species (Coccinellidae) and common green lacewing *Chrysoperla carnea* was similar between intercropped (12.5-13.0 eggs and 1.5-1.7 pupae per plant) and monoculture (11.5 eggs and 1 pupa) plots. Aphid (Aphidoidea) abundance was significantly lower in intercropped (110-125 per lettuce plant) than monoculture (160 per plant) plots. Natural predator and aphid numbers were similar between plots intercropped with wormwood *Artemisia vulgaris*, tansy *Tanacetum vulgare* or stinging nettle *Urtica dioica*. The attractant plants were tested separately in three blocks inside a 6 x 50 m field. Each attractant plant species was grown in nine plots of 1 x 0.3 m, placed in a 3 x 3 grid among 20 lettuce rows.

A replicated, randomized and controlled study in 1998–1999 in western Kenya (*2*) found that larval and pupal parasitism of four pest stem borer species (Crambidae, Noctuidae and Pyralidae) by four parasitoid wasp species (Hymenoptera) was similar in plots of sorghum *Sorghum bicolor* intercropped with molasses grass *Melinis minutiflora* (4.4% parasitism) and plots of sorghum monoculture (5.1% parasitism). Parasitism differed for only one of four seasons (in 1998), when pupal parasitism was higher in monoculture plots. The spotted borer *Chilo partellus* was less abundant in intercropped plots (2,750 individuals) than in monoculture plots (3,601). Intercropped plots contained one row of

molasses grass for every three sorghum rows. Plots were 9 x 10 m with the treatment replicated in 11 blocks over three fields. Laboratory studies of odour choice found that volatiles from sorghum or maize *Zea mays* with molasses grass were not more attractive to the stem borer parasitoid sp. *Cotesia sesamiae* than maize or sorghum volatiles alone. The parasitoid *Dentichasmias busseolae* was repelled by molasses grass volatiles.

A controlled study in 2001-2003 in Guangzhou, China (*3*) found that more predatory mites *Amblyseius newsami* occurred in orange *Citrus sinensis* orchards with a tropical whiteweed *Ageratum conyzoides* ground cover (0.3 mites/orange tree leaf) than in control orchards (0.09 mites). The pest citrus red mite *Panonychus citri* was also less numerous in orchards containing tropical whiteweed (0.03 mites/leaf) than control orchards (0.18 mites). Odour choice tests in the laboratory found that *Amblyseius newsami* was strongly attracted to volatiles from fresh leaves (61% of choices versus a control) or essential oils (95% of choices) from tropical whiteweed. The study compared an orchard with a tropical whiteweed understorey grown for two years, and a control orchard with a groundcover of naturally growing weed species (but with tropical whiteweed removed). Mite counts took place in June 2003 using 15 randomly selected orange trees.

A replicated, randomized, controlled study in 2006-2007 in Karnataka, India (*4*) found more natural predators including, lacewing (Neuroptera) eggs and ladybirds (Coccinellidae), in safflower *Carthamus tinctorious* intercropped with 7-13% coriander *Coriandrum sativum* (6.0-7.6 lacewing eggs and 1.0-1.4 ladybirds/plant) than in safflower monoculture (4.8 and 0.8, respectively). Cotton bollworm *Helicoverpa armigera* damage was lowest in intercropped plots of 13% and 10% coriander (16-17% of safflower capsules damaged) and greatest in safflower monoculture plots (21% damaged). Safflower yield was greater (0.92-1.1 t/ha) in intercropped plots (at all densities of coriander) than in monoculture plots (0.86 t/ha). The experiment comprised four treatments (safflower mixed with coriander at 5%, 7%, 10% and 13% of sowing seed volume) and a safflower monoculture control, replicated three times.

(1) Sengonca C., Kranz J. & Blaeser P. (2002) Attractiveness of three weed species to polyphagous predators and their influence on aphid populations in adjacent lettuce cultivations. *Anzeiger Fur Schadlingskunde-Journal of Pest Science*, 75, 161-165.

(2) Gohole L.S. (2003) Enhancing foraging behaviour of stemborer parasitoids: role of a non-host plant, *Melinis minutiflora*. PhD thesis. University of Wageningen.

(3) Kong C.H., Hu F., Xu X.H., Zhang M.X. & Liang W.J. (2005) Volatile allelochemicals in the *Ageratum conyzoides* intercropped citrus orchard and their effects on mites *Amblyseius newsami* and *Panonychus citri*. *Journal of Chemical Ecology*, 31, 2193-2203.

(4) Hanumantharaya L., Venkateshalu, Kubasad V.S. & Raju S.G. (2008) Role of cropping pattern for the management of insect pests of safflower, *Carthamus tinctorius* L. *Proceedings of the 7th International Safflower Conference*. Wagga Wagga, Australia, pp 1-4.

3.5. Use chemicals to attract natural enemies

- **Parasitism and predation** (by natural enemies)**:** One review[15] and two[9,13] of five studies from Asia, Europe and North America found that attractive chemicals increased parasitism. Two studies[2,8], including one randomized, replicated, controlled trial, found greater parasitism for some but not all chemicals, crops, sites or years and one study

found no effect[14]. One study[8] showed that parasites found pests more rapidly. One study[6] found lower egg predation by natural predators.

- **Natural enemies:** Five[1,3,5,7,13] of 13 studies from Africa, Asia, Australasia, Europe and North America found more natural enemies while eight[4,6,8,10,11,12,14,15] (including seven randomized, replicated, controlled trials) found positive effects varied between enemy groups, sites or study dates. Four[10,11,12,15] of 13 studies (including a meta-analysis) found more natural enemies with some but not all test chemicals. Two[10,15] of four studies (including a review) found higher chemical doses attracted more enemies, but one study[4] found lower doses were more effective and one[8] found no effect.
- **Pests:** Three[5,6,13] of nine studies (seven randomized, replicated, controlled) from Asia, Australasia, Europe and North America found fewer pests, although the effect occurred only in the egg stage in one study[6]. Two studies[4,7] found more pests and four[3,11,12] found no effect.
- **Crop damage:** One study[12] found reduced damage with some chemicals but not others, and one[6] study found no effect.
- **Yield:** One study[13] found higher wheat yields.
- **Crops studied** were apple[10], banana[8], bean[3], broccoli[6,12,15], Chinese cabbage[14], cotton[1,15], cowpea[2], cranberry[11], grape[4,8,12], grapefruit[8], hop[4,15], maize[2,12], oilseed[13], orange[5,8], tomato[2], turnip[7] and wheat[13].

Background

This involves using chemicals to lure natural enemies into a crop. Communication chemicals of insects and plants (known as pheromones and volatiles, respectively) can be manufactured and deployed to manipulate invertebrates. Examples include the volatiles produced when plants are attacked by pests (e.g. methyl salicylate) and the alarm and sex pheromones of pests or natural enemies, as well as organic extracts from crop or plant leaves. Chemicals are sprayed onto crops or deployed in dispensers placed at regular intervals in the crop. Many studies have tested the efficacy of chemicals by applying them as baits in insect traps such as delta traps (plastic structures hung from branches or posts containing a sheet of sticky paper). Ground-living invertebrates can be sampled by suction sampling, using a vacuum to suck-up and collect specimens for a given time or area of ground.

A controlled, paired study in Egypt (*1*) found three times more insect predators in cotton *Gossypium* sp. fields treated with pink bollworm *Pectinophora gossypiella* mating-disruption chemicals (sex pheromones) than in controls treated with insecticide. Average daily moth (Lepidoptera) catches were lower and seed cotton yields were higher in fields treated with pheromones than in controls. Three sex pheromone formulations were tested (microcapsules in solution, laminated plastic chips and hollow fibres) but average moth catches and yield were unaffected by these treatments. Pheromone treatments were tested in three 50 ha blocks of cotton, each paired with a 50 ha insecticide-treated control. Natural enemies were monitored by D-vac sampling. Moths were monitored in pheromone-baited traps and by counting infested flowers and cotton bolls. This conference paper did not determine whether natural enemies

were attracted to the pheromones or simply benefited from the absence of insecticides.

A replicated, controlled field study (*2*) found greater corn earworm *Helicoverpa zea* parasitism in plots of corn *Zea mays* treated with tomato *Solanum lycopersicum* extract (38% eggs parasitized) than in control plots of corn without tomato extract (29%). Eggs were parasitized by the wasp *Trichogramma pretiosum*. Parasitism was similar in plots of tomato treated with corn extract (53% eggs parasitized) and controls of tomato without corn extract (54%). A greenhouse experiment found the wasp also parasitized more corn earworm eggs in pots of cowpea *Vigna unguiculata* treated with tomato extract (52-74% eggs parasitized) than in pots treated with corn extract (19-26%) or untreated controls (18-26%). A lab study found similar results by monitoring parasitism in petri dishes containing the extracts. Plant extracts were obtained by grinding fresh leaves. In the field study extracts were sprayed (at 2 g/plot in 10 ml of hexane) on 1 row by 3 m plots. Controls were left unsprayed. Corn and tomato extract treatments were replicated 30 and 40 times, respectively. Corn earworm eggs were placed at 0.3 m intervals, 50 parasitoid wasps were released and eggs were collected after four hours. The greenhouse trial grew cowpea in 28.8 cm pots.

A replicated study in 1995 in Maryland, USA (*3*) found more predatory spined soldier bugs *Podisus maculiventris* in six green bean *Phaseolus vulgaris* rows positioned close to pheromone chemical dispensers (averaging 4 immature spined soldier bugs) than in six bean rows further away (1 immature). More spined solider bugs were recovered in the six closest (0.0-4.5% recovered) than the six farthest (0.0-1.4%) bean rows at four and seven days after their release, but numbers were similar one day after their release (0.0-1.3 vs 0.0-1.6%). Numbers of the pest Mexican bean beetle *Epilachna varivestis* were similar in the six closest (11-20 larvae/row) and six farthest (5-39 larvae) rows from the pheromone dispensers. Immature spined solider bug were also attracted to the pheromone in a wind tunnel experiment. Three Soldier Bug Attractors (dispensers containing a pheromone produced by adult male spined solider bugs) were placed along one edge of a 13-row plot of green beans. Immature spined solider bugs were released into the middle row of the plot (averaging 261 individuals/plot) and monitored to assess their spread towards or away from the dispensers. Plots were 9.7 x 6.3 m and replicated seven times.

A randomized, replicated, controlled trial in 2004 in Washington State, USA (*4*) found more parasitic wasps from the genus *Metaphycus* in vineyard blocks baited with three chemical treatments (averaging 12-25 wasps/shake sample/week) than in unbaited controls (8 wasps). Chemicals attracted more wasps from the genus *Anagrus* than controls in 1-3 of the five months, but numbers were only greater in all three treatments in September (approximately 260-290 vs 170-175 wasps/trap/week). A replicated, paired, controlled trial found hops *Humulus lupulus* with methyl salicylate had 3-5 times more predatory insects than unbaited hops. Hops with a low methyl salicylate deployment rate had more predators vs hops with high deployment (106 vs 46 predators/shake sample/week). Pest spider mites (Tetranychidae) briefly exceeded spraying thresholds in baited but not unbaited hops. Predators were scarce in vineyards but some groups, including hoverflies (Syrphidae), lacewings (Chrysopidae) and lady beetles *Stethorus* spp., were more numerous in baited

than unbaited vineyards. The first study compared methyl salicylate, methyl jasmonate and (Z)-3-hexenyl acetate treatments with unbaited controls, replicated in three 8 x 30 m vineyard blocks. The second study tested methyl salicylate at rates of 0, 180 and 516-556 dispensers/ha in hops and vineyards.

A controlled study in 2003 in Guangzhou, China (*5*) found that more predatory mites *Amblyseius newsami* occurred in orange *Citrus sinensis* trees treated with essential oils of tropical whiteweed *Ageratum conyzoides* (0.41 mites/leaf) than on control trees (0.09 mites) after 24 hours. However, 48 hours after treatment, numbers of predatory mites had dropped to 0.13 mites/leaf. Fewer pest citrus red mites *Panonychus citri* were found on treated (0.05 mites/leaf) than control (0.18 mites) trees after 24 hours, but numbers increased to 0.19 mites/leaf on treated trees after 48 hours. A 5% emulsion of tropical whiteweed essential oil and a water control were applied to 18 and nine orange trees, respectively. All trees were more than 15 m apart. The authors found that a tropical whiteweed ground cover increased predatory mite numbers (see 'Grow non-crop plants that produce chemicals that attract natural enemies') and they suggest this may attract the predator for longer than using essential oils.

A randomized, replicated, controlled study in 2007 in Saint Méloir des Ondes, France (*6*) found lower cabbage fly *Delia radicum* egg predation in broccoli *Brassica oleracea* plots with dimethyl disulphide lures (2.1 eggs predated/patch of eggs) than in controls without the chemical (2.6 eggs). More rove beetles (*Aleochara bilineata* and *A. bipustulata*) occurred in treated plots (119 and 107 individuals, respectively) than controls (21 and 69 individuals) and numbers were highest in pitfall traps closest to the chemical attractant. More ground beetles *Bembidion* spp. occurred in treated plots (539 individuals) than controls (462 individuals) but this effect varied with sampling date and there was no effect of distance from the chemical. Fewer cabbage fly eggs were found in treated plots than controls (4 vs 11 eggs/plant), but larvae and pupae numbers were similar. Fly damage to broccoli was similar in the two treatments. Tubes of dimethyl disulphide diluted in paraffin were placed beside broccoli plants in treated plots. Controls used tubes of pure paraffin. Treatments were replicated four times in 14 x 15 m plots. Egg predation was measured by placing 16 patches of eggs (5 eggs/patch) into each plot for 48 hours and counting missing/chewed eggs.

A randomized, replicated, controlled study in 2007 in Canterbury, New Zealand (*7*) found higher numbers of the parasitoid wasp *Diadegma semiclausum* in turnip *Brassica rapa* plots with a methyl salicylate lure (averaging 1.6-7.2 wasps/trap) than in controls without the chemical (1.4-6.4 wasps). Other natural enemies, including brown lacewings *Micromus tasmaniae* and hoverflies (Syrphidae), were captured too infrequently to be analysed. More pest leaf miners *Scaptomyza flava* occurred in plots with the chemical attractant (2-17 leaf miners/trap) than controls (1-12 leaf miners). The parasitic wasp *Anacharis zealandica*, an enemy of beneficial brown lacewings, was also more abundant in plots with methyl salicylate (0.0-3.3 wasps/trap) than in controls (0.0-1.2 wasps). The authors suggest that attracting beneficial insects with chemicals can also attract potentially harmful insects. One sachet of synthetic methyl salicylate was hung above treated plots and was replenished twice during the study period (24 April to 12 June 2007). No chemical was used in controls. Treated and

control plots were replicated 12 times in a 400 x 470 m field. Natural enemies, pests and parasites of natural enemies were monitored using yellow sticky traps.

A randomized, replicated, controlled experiment in 2006-2008 in Israel, Italy and Portugal (*8*) found greater citrus mealybug *Planococcus citri* parasitism in traps with lavandulyl senecioate lures (19-51 parasitoid wasps *Anagyrus* sp. emerged from citrus mealybugs/trap) than in control traps (0-20 wasps emerged) in seven of 10 trials. Parasitism was similar between traps in three trials (5-10 vs 2-4 wasps emerged). Wasps took 1.6-3.5 fewer days to emerge from mealybugs collected from baited than from control traps, suggesting wasps had found baited traps more rapidly. More parasitoid wasps were found in baited (1-16 females/trap) than control (0-2 females) traps in five of nine trials, but very few wasps occurred in the four other trials (in both treatments). Parasitism levels and wasp numbers were similar between traps with lavandulyl isovalerate lures and control traps in four trials, and similar between traps with planococcyl acetate lures and controls in six out of seven trials. The dose of lavandulyl senecioate (ranging 25-1,000 µg) did not affect wasp numbers. The chemicals (all naturally released by mealybugs) were tested in citrus and banana plantations and vineyards at seven locations. Each treatment was replicated 5-14 times per site.

A controlled, replicated study in 1999 in Ibaraki Prefecture, Japan (*9*) found greater parasitism of brown-winged green bugs *Plautia stali* in traps with an attractive chemical (6.0% individuals parasitized) than in control traps with light lures (2.7% parasitized). Parasitic flies *Gymnosoma rotundatum* were attracted to a chemical (methyl-2,4,6-decatrienoate) naturally produced by male brown-winged green bugs. In a separate experiment manipulating groups of bugs, the fly *G. rotundatum* parasitized 1-17% of bugs baited with the chemical compared to 0% for unbaited bugs. Monitoring from 2000 to 2005 found much fewer parasitic flies (approximately 25-95 adults captured at peak numbers) than brown-winged green bugs (260-9,710 adults) were attracted to traps with chemical lures. From April to November 1999, water-basin traps with 85 mg of methyl-2,4,6-decatrienoate were placed in Japanese paulownia *Paulownia tomentosa* trees and catches were compared with light traps (using 100 W mercury vapour lamps). In the second experiment (repeated six times) groups of 10 brown-winged green bugs were attached to frames with and without chemical lures and parasitism was monitored. Monitoring in 2000-2005 tested the lure in 2-5 water-basin traps/year from April to November.

A randomized, replicated, controlled study in 2008 in four apple *Malus domestica* orchards in Washington State, USA (*10*) found more green-eyed lacewings *Chrysopa oculata* (8-145 lacewings/trap) and green lacewings *Chrysopa nigricornis* (86-446 lacewings) in trees with iridodial-methyl salicylate lures than control trees without lures (0-3 and 0-7 lacewings, respectively). Benzaldehyde attracted higher numbers of the lacewing *Chrysopa plorabunda* in treated (6-64 lacewings/trap) compared to control trees (0-1 lacewings), but had little effect on green-eyed and green lacewing captures. Across all three species, there were mixed effects of iridodial alone, methyl salicylate alone, cis-3-hexen-1-ol and cis-3 hexenyl acetate. An additional experiment in two orchards found that squalene lures or mixed lures containing this chemical attracted more green lacewings (8-24 lacewings/trap day) than iridodial-methyl salicylate lures (2-4 lacewings). More green lacewings were caught with higher squalene doses.

Six chemical lures (in 5-cm diameter plastic tubing) were placed in white plastic delta traps and compared with control traps containing distilled water. Each treatment was replicated four times in each orchard. Delta traps and lures were placed 1.5-3.0 m high in the canopy and lacewing captures were monitored 1-2 times/week.

A randomized, replicated, controlled study in 2008-2009 in cranberry *Vaccinium macrocarpon* bogs in New Jersey, USA (*11*) found 4.5 times more hoverflies (Syrphidae), 1.8 times more lady beetles (Coccinellidae) and 7.6 times more green lacewings (Chrysopidae) in traps baited with methyl salicylate lures than in controls with no chemical. Baited traps had more hoverflies for seven of eight weeks but lady beetle and lacewing numbers were higher for only two of eight weeks. Flower bug (Anthocoridae), parasitoid fly (Tachinidae) and pest leafhopper (Cicadellidae) numbers were similar in the baited and control traps. In 2009, hoverflies were 84% more abundant in traps containing lures than in controls, but there was no effect for traps placed 2.5, 5 or 10 m away from lures. There was no effect of methyl salicylate on lady beetle numbers in 2009. A meta-analysis found 91 observations from 14 studies testing methyl salicylate lures on 34 natural enemy species (across nine crop types). Forty-one observations showed positive effects of lures and 50 showed no effect. The 2008 study applied single baited and control traps to 15 cranberry bogs, the 2009 study included 10 bogs (5 with lures, 5 with controls).

A randomized, replicated, controlled study in 2008-2009 in New South Wales, Australia (*12*) found effects of attractant chemicals varied between crops and natural enemy groups. More predators occurred in broccoli *Brassica oleracea* treated with a mix of plant chemicals (2.5 predators/trap/day) than for water-treated controls (1.8 predators) one day after spraying. Attractants did not affect total predator numbers in sweetcorn *Zea mays* or grapevine *Vitis vinifera* and total parasitoid numbers were unaffected in all three crops. Two parasitoid wasp families (Ceraphronidae and Seclionidae) were attracted to one of four chemicals tested in broccoli and two families (Encyrtidae and Eulophidae) were attracted to one and all attractants respectively, tested in sweetcorn. However, some effects were short-lived or depended on the additional presence of attractive plants. Other natural enemy groups (including up to 11 parasitoid families and 10 predator groups) were not affected by chemical attractants. Butterflies and moths (Lepidoptera) and leafhoppers (Cicadellidae) were not attracted to plots with chemicals. Damage by moth larvae *Helicoverpa* sp. was lower in sweetcorn treated with methyl anthranilate attractant (1.5% sweetcorn damaged) than in controls (2.7%), but other chemicals had no effect. The study tested five plant chemicals (methyl anthranilate, methyl jasmonate, methyl salicylate, cis-3-hexenyl acetate and benzaldehyde) and two mixes of chemicals.

A randomized, replicated, controlled study in 2008-2009 in Shandong, China (*13*) found greater parasitism of English grain aphid *Sitobion avenae* in wheat *Triticum aestivum* plots containing methyl salicylate lures (averaging 23-26% aphids parasitized) than in controls without lures (18-19%). Aphid parasitism by wasps (Aphidiidae) increased to 27-29% when the chemical was released in wheat-oilseed rape *Brassica napus* intercrops. More predatory lady beetles (Coccinellidae) occurred in wheat monocrop and intercrop plots with lures (13-16 and 16-20 lady beetles/100 shoots, respectively) than in the monocrop control without lures (9-11 lady beetles). Fewer English grain aphids were found

in plots with lures (approximately 455-520 and 345-380 aphids/100 shoots, in monoculture and intercropped plots respectively) than in the control (870-920 aphids). Wheat yields were also higher in plots with methyl salicylate lures (5.7-6.1 and 6.4-6.7 t/ha in monoculture and intercropped plots, respectively) compared to the control (5.3-5.4 t/ha). The study compared four treatments replicated three times: wheat monocrop (control), monocrop with methyl salicylate, wheat-oilseed rape intercrop, and intercrop with methyl salicylate. Methyl salicylate was released from one slow-release dispenser/plot at 120 mg/m^2/week. Plots were 10 x 10 m and insects were monitored on 10 shoots at 10 sample sites/plot.

A randomized, replicated, controlled study in 2009-2010 in Shandong, China (*14*) found plots with E-β-farnesene lures had 9-41 parasitized aphids/20 Chinese cabbages *Brassica rapa pekinensis* compared to 5-19 parasitized aphids in controls. More parasitoid wasps (Aphidiidae) occurred in plots with the chemical attractant (11-14 wasps in traps) than controls (5-10 wasps). More lady beetles occurred on cabbages in treated versus control plots (14-16 vs 6-8 lady beetles/20 cabbages), but numbers were similar in traps (2.4-3.0 vs 0.7-2.7 lady beetles). Spider (Araneae) numbers were similar between treated plots (26-133 spiders/20 cabbages) and controls (60-104 spiders). Fewer aphids (Aphidoidea) occurred in plots with E-β-farnesene lures than controls (167 vs 365 aphids/20 cabbages in 2009, 1,108 vs 1,332 in 2010). A chemical releaser was attached to a yellow pan trap in the centre of each 10 x 10 m plot and filled with 100 µl of E-β-farnesene (an aphid alarm chemical) in paraffin oil every seven days. Controls used a pan trap with no chemical releaser. Treatments were replicated three times. Invertebrates were surveyed weekly in September-October on 20 cabbages and in pan traps.

A review (*15*) of 35 studies found that 29 of 37 tested plant chemicals attracted and increased numbers of at least some natural enemy species or groups, although most chemicals also led to no response from other species or groups. One study (Titayavan & Altieri 1990) found that aphid (Aphidoidea) parasitism increased from 8.5% to 22.5% when broccoli *Brassica oleracea* was treated with allyl isothiocyanate. Williams *et al.* (2008) found two to three times more tarnished plant bug *Lygus lineolaris* egg parasitism when the chemicals (Z)-3-hexenyl acetate and α-farnesene were applied to cotton *Gossypium hirsutum*. One study (James & Price 2004) found densities of predatory insects were four times greater in hops *Humulus lupulus* baited with methyl salicylate compared to unbaited controls. Average numbers of minute pirate bugs *Orius tristicolor* and spider mite destroyers *Stethorus punctum picipes* were seven and 57 times greater (respectively) in baited than unbaited plots across the season. Another study in cotton (Flint *et al.* 1981) found that predatory beetle *Collops vittatus* numbers increased (from 0 to 2.7, 3.3 and 7.6 trap catches) as doses of synthetic caryophyllene oxide increased (0.0, 0.1, 1.0 and 10.0 g, respectively). James (2006) also found a dosage effect, with twice as many green lacewings *Chrysopa oculata* on traps baited with 99% methyl salicylate compared with 1% and 10% dilutions.

(1) McVeigh L.J., Critchley B.R. & Campion D.G. (1983) Control of the pink bollworm in Egypt by mating disruption using pheromones. *Proceedings of the 10th International Congress of Plant Protection: Plant Protection for Human Welfare, 20-25 November, 1983*. Brighton, UK, Vol 1, p 268.

(2) Nordlund D.A., Chalfant R.B. & Lewis W.J. (1985) Response of *Trichogramma pretiosum* females to extracts of two plants attacked by *Heliothis zea*. *Agriculture, Ecosystems & Environment*, 12, 127-133.
(3) Sant'Ana J., Bruni R., Abdul-Baki A.A. & Aldrich J.R. (1997) Pheromone-induced movement of nymphs of the predator, *Podisus maculiventris* (Heteroptera: Pentatomidae). *Biological Control*, 10, 123-128.
(4) James D.G., Castle S.C., Grasswitz T. & Reyna V. (2005) Using synthetic herbivor-induced plant volatiles to enhance conservation biological control: field experiments in hops and grapes. *Proceedings of the Second International Symposium on Biological Control of Arthropods, September 12-16, 2005*. Davos, Switzerland, Vol 1, pp 192-205.
(5) Kong C.H., Hu F., Xu X.H., Zhang M.X. & Liang W.J. (2005) Volatile allelochemicals in the *Ageratum conyzoides* intercropped citrus orchard and their effects on mites *Amblyseius newsami* and *Panonychus citri*. *Journal of Chemical Ecology*, 31, 2193-2203.
(6) Ferry A., Le Tron S., Dugravot S. & Cortesero A.M. (2009) Field evaluation of the combined deterrent and attractive effects of dimethyl disulfide on *Delia radicum* and its natural enemies. *Biological Control*, 49, 219-226.
(7) Orre G.U.S., Wratten S.D., Jonsson M. & Hale R.J. (2010) Effects of an herbivore-induced plant volatile on arthropods from three trophic levels in brassicas. *Biological Control*, 53, 62-67.
(8) Franco J.C., da Silva E.B., Fortuna T., Cortegano E., Branco M., Suma P.*, et al.* (2011) Vine mealybug sex pheromone increases citrus mealybug parasitism by *Anagyrus* sp. near *pseudococci* (Girault). *Biological Control*, 58, 230-238.
(9) Higaki M. & Adachi I. (2011) Response of a parasitoid fly, *Gymnosoma rotundatum* (Linnaeus) (Diptera: Tachinidae) to the aggregation pheromone of *Plautia stali* Scott (Hemiptera: Pentatomidae) and its parasitism of hosts under field conditions. *Biological Control*, 58, 215-221.
(10) Jones V.P., Steffan S.A., Wiman N.G., Horton D.R., Miliczky E., Zhang Q.H.*, et al.* (2011) Evaluation of herbivore-induced plant volatiles for monitoring green lacewings in Washington apple orchards. *Biological Control*, 56, 98-105.
(11) Rodriguez-Saona C., Kaplan I., Braasch J., Chinnasamy D. & Williams L. (2011) Field responses of predaceous arthropods to methyl salicylate: a meta-analysis and case study in cranberries. *Biological Control*, 59, 294-303.
(12) Simpson M., Gurr G.M., Simmons A.T., Wratten S.D., James D.G., Leeson G.*, et al.* (2011) Attract and reward: combining chemical ecology and habitat manipulation to enhance biological control in field crops. *Journal of Applied Ecology*, 48, 580-590.
(13) Wang G., Cui L., Dong J., Francis F., Liu Y. & Tooker J. (2011) Combining intercropping with semiochemical releases: optimization of alternative control of *Sitobion avenae* in wheat crops in China. *Entomologia Experimentalis et Applicata*, 140, 189-195.
(14) Cui L., Francis F., Heuskin S., Lognay G., Liu Y., Dong J.*, et al.* (2012) The functional significance of E-β-Farnesene: does it influence the populations of aphid natural enemies in the fields? *Biological Control*, 60, 108-112.
(15) Kaplan I. (2012) Attracting carnivorous arthropods with plant volatiles: the future of biocontrol or playing with fire? *Biological Control*, 60, 77-89.

Additional references

Flint H.M., Merkle J.R. & Sledge M. (1981) Attraction of male *Collops vittatus* in the field by caryophyllene alcohol. *Environmental Entomology*, 10, 301-304.
Titayavan M. & Altieri M.A. (1990) Synomone-mediated interactions between the parasitoid *Diaeretiella rapae* and *Brevicoryne brassicae* under field conditions. *Entomophaga*, 35, 499-507.
James D.G. & Price T.S. (2004) Field-testing of methyl salicylate for recruitment and retention of beneficial insects in grapes and hops. *Journal of Chemical Ecology*, 30, 1613-1628.
James D.G. (2006) Methyl salicylate is a field attractant for the goldeneyed lacewing, *Chrysopa oculata*. *Biocontrol Science and Technology*, 16, 107-110.
Williams L., Rodriguez-Saona C., Castle S.C. & Zhu S. (2008) EAG-active herbivore induced plant volatiles modify behavioral responses and host attack by an egg parasitoid. *Journal of Chemical Ecology*, 34, 1190-1201.

3.6. Use mass-emergence devices to increase natural enemy populations

- **Parasitism:** One randomized, replicated, controlled study[1] in Switzerland found higher parasitism at one site but no effect at another site when mass-emergence devices were used in urban areas.
- **Pest damage:** The same study[1] found no effect on pest damage to horse chestnut trees.

Background

Mass-emergence devices are containers giving natural enemies a sheltered environment and a food or prey source (such as pollen or pests on infested foliage), enabling enemy numbers to establish before emerging from the device and dispersing into the crop. Designs may include size-selective exits, preventing pests but allowing natural enemies (such as parasitoid wasps) to leave and disperse. Conventional practices of removing and destroying pest-infested crop foliage can reduce natural enemy numbers, but using the foliage in mass-emergence devices instead may relocate natural enemies back into the crop.

We found no studies testing this action in a farmed environment, but one study of urban trees is presented here as preliminary evidence.

A randomized, replicated, controlled study in 2003 at two urban sites in Bern, Switzerland (*1*) found higher parasitism of horse chestnut leafminers *Cameraria ohridella* in trees with mass-emergence devices (averaging 5-16% leafminers parasitized) than control trees without devices (3-10%) at one site and for a March (rather than May) application date. There was no effect of mass-emergence devices (or timing of application) at the second site (4-14% leafminers parasitized in treated trees vs 5-15% in controls). Leaf loss caused by leafminers was similar in mass-emergence (3-54% defoliation) and control (3-63%) trees at both sites. Devices were placed in horse chestnut *Aesculus hippocastanum* trees to control leafminer damage using parasitoid wasps (Hymenoptera). Devices were 200 l plastic tubs with four openings covered in a tissue filter with 600 µm mesh size – allowing wasps (but not leafminers) to develop, emerge and disperse into the trees. Horse chestnut leaf litter containing leafminers and parasitoids was placed inside the tubs (10 kg/device). Ten blocks of horse chestnut trees were selected (five at each site) and devices were hung in three trees/block. Two trees had devices (1 device/tree, applied 20 March and 23 May, respectively) and a control tree had no device.

(1) Kehrli P., Lehmann M. & Bacher S. (2005) Mass-emergence devices: a biocontrol technique for conservation and augmentation of parasitoids. *Biological Control*, 32, 191-199.

4. Arable farming

4.1. Create beetle banks

- **Natural enemies in fields:** Six studies from Canada, the UK and USA (three replicated, controlled, of which two were also randomized) examined the effects on predator numbers in adjacent crops. A review[8] found that predators increased in adjacent crops, but one study[10] found effects varied with time and another[6] found no effect. Two studies[1,2,11] found small or slow movements of predators from banks to crops. One study[17] found greater beetle activity in fields but this did not improve pest predation.
- **Natural enemies on banks:** Four studies[1,2,6,7,13] and a review[18] found more invertebrate predators on beetle banks than in surrounding crops, but one of these found that effects varied with time.

  Eight studies from the UK and USA (including two randomized, replicated, controlled trials and two reviews) compared numbers of predatory invertebrates on beetle banks with other refuge habitats. Two studies[2,7] found more natural enemies on beetle banks, but one of these[14] found only seasonal effects. One review[18] found similar or higher numbers of predators on beetle banks and four studies found similar[3,9] or lower[4,5,9,16] numbers.
- **Pests:** A replicated, randomized, controlled study[11] and a review[18] found the largest pest reductions in areas closest to a beetle bank or on the beetle bank itself. One review[7] found fewer pests in fields with than without a beetle bank.
- **Economics:** One replicated, randomized, controlled trial and a review[2,7] showed that beetle banks could make economic savings if they prevented pests from reaching a spray threshold or causing 5% yield loss.
- **Beetle bank design:** Two studies[4,5,15,16] from the UK found certain grass species held higher numbers of predatory invertebrates than others.
- **Crops studied** were barley[1,3,13,18], field bean[13], maize[6], oats[6], pasture[13], pea[3], radish[17], rapeseed[3,13], soybean[6,7] and wheat[1,2,3,7,11,13,16,18].

Background

Beetle banks are raised strips which run through a field, typically planted with grasses. They primarily serve as an overwintering habitat for beetles, which provide pest control in the spring, but may also harbour other natural enemies. By dividing the field, beetle banks reduce the distance that predators have to travel to reach the centre of the crop, a potential problem if overwintering habitat occurs only at the field edge. Beetles are frequently surveyed using pitfall traps, but these measurements relate to both the abundance of beetles and their levels of activity on the ground; pitfall trap data therefore refer to 'activity densities'.

A replicated, randomized study in spring 1988-1990 on a beetle bank in a 7 ha winter wheat *Triticum* sp. field in Hampshire, UK (*1*) found that over the 1988 survey period, predatory invertebrate activity shifted from the beetle bank into the crop, although the effect was small. In 1989, the ground beetle *Demetrias*

atricapillus was initially more abundant 0-3 m from the beetle bank (average 12.2 individuals/m^2, 14 April-3 May) but became more evenly distributed with an average 0.4 individuals/m^2 at 0-60 m from the bank (8-22 May). The rove beetle *Tachyporus hypnorum* did not show a consistent distribution in 1989-1990, although fewer individuals were found on the bank than the crop by the end of the 1989 survey. More money spiders (Linyphiidae) were found in the beetle bank than the crop in 1989 and in 1990 there was a slight emigration of money spiders away from the bank into the crop. In 1990 wolf spiders (Lycosidae) were found throughout the crop but were most abundant next to the beetle bank. The beetle bank (290 m long, 0.4 m high and 1.5 m wide) was created in autumn 1986 and sown with grasses. This study was part of the same experimental set-up as (*2*), (*3*), (*4*) and (*16*).

A randomized, replicated, controlled study in winter 1987-1988 and 1988-1989 on two beetle banks in two cereal fields on a farm in Hampshire, UK (*2*) found total invertebrate predator numbers collected from turf samples and ground searching were higher on beetle banks (218-1,488 individuals/m^2 in turf samples, 39-188 individuals/m^2 in surface searches) than the surrounding crop (26-29 individuals/m^2 in turf samples, 16-49 individuals/m^2 in surface searches). Invertebrate predators included ground beetles (Carabidae), rove beetles (Staphylinidae) and spiders (Araneae). In 1989, emigration patterns of the rove beetle *Tachyporus hypnorum* and the ground beetle *Demetrias atricapillus* showed movement of individuals from the bank into the field from 14 April-22 May. From 14 April-3 May, there were 12.2 individuals/m^2 of *D. atricapillus* at 0-3 m from the bank, after which the average density was 0.4 individuals/m^2 at 0-60 m from the bank. By the end of the study there were significantly fewer *T. hypnorum* on the bank than the crop. Establishment costs were estimated at £85 in year one and £30 in following years for a 20 ha field (1990 prices). Maintaining aphid (Aphidoidea) populations below a spray threshold was valued at £300/year and £660/year if an aphid-induced yield loss of 5% was prevented. This study was part of the same experimental set-up as (*1*), (*3*), (*4*) and (*16*).

A randomized, replicated, controlled study over three winters from 1987-1990 on two farms in Hampshire, UK (*3*) (part of the same study as (*2*) but extended to a third winter and a third beetle bank in a 51 ha field on a second farm) found that three years after beetle bank establishment, total predator densities on beetle banks (358-764 individuals/m^2) were not different to those in natural field boundaries (541-569 individuals/m^2). Ground beetle and spider community composition was similar between beetle banks and field boundaries. Cock's-foot *Dactylis glomerata*, a tussock-forming grass, supported highest densities of ground beetles in the third winter. Community composition of ground beetles and spiders changed during the study to species that prefer boundary or more permanent habitats. Banks were 0.4 m high x 1.5 m wide. Two were 290 m long in 7 and 20 ha fields, one was 580 m long in a 51 ha field. One field was sown with winter wheat *Triticum* spp. throughout the study, one field had winter wheat then fodder pea *Pisum sativum* and winter rape *Brassica napus*, and one field had spring barley *Hordeum vulgare* then vining peas. This study was part of the same experimental set-up as (*1*), (*2*), (*4*) and (*16*).

A replicated study over seven winters from late 1987 to early 1994 on one beetle bank in Hampshire and one in Essex, UK (*4*) found sections sown with the

grasses cock's-foot *Dactylis glomerata* or Yorkshire fog *Holcus lanatus* generally had highest densities of predatory invertebrates, but not always significantly so. Ground beetles (Carabidae) and rove beetles (Staphylinidae) had higher densities in cock's-foot (11-110 ground beetles/m^2, 1-125 rove beetles) and Yorkshire fog (1-76 ground beetles/m^2, 2-113 rove beetles) than two other grass species (2-15 ground beetles/m^2, 0-79 rove beetles). Ground beetle and rove beetle densities peaked in the second and sixth winters after banks were established. The pattern was the same for spiders (Araneae) in cock's-foot but in Yorkshire fog, creeping bent *Agrostis stolonifera* and perennial ryegrass *Lolium perenne* the densities steadily increased to a maximum in the fifth winter. The 200 m long beetle bank in Essex had a lower density of ground beetles than a nearby hedge bottom (0.7 individuals/m^2 vs 2.6 individuals). The 290 m long Hampshire beetle bank was created in spring 1987 and split into six blocks, each further sub-divided into eight plots with one sown grass treatment/plot. This study was part of the same experimental set-up as (*1*), (*2*), (*3*) and (*16*).

A replicated study in the winters of 1993-1996 in Leicestershire, UK (*5*) found a beetle bank had lower densities of invertebrate predators (total of all groups combined), ground beetles (Carabidae) and rove beetles (Staphylinidae) than a nearby hedge across the study period. Total predator, ground beetle and rove beetle densities increased with age of beetle bank and by the third winter there were similar total predator and ground beetle densities between the hedge and beetle bank. Spider (Araneae) densities were similar between habitats. Total predator, ground beetle and rove beetle densities on beetle banks were highest in false oat grass *Arrhenatherum elatius*, cock's-foot *Dactylis glomerata* and timothy *Phleum pratense*. Densities were lowest in crested dog's-tail *Cynosurus cristatus*. In the first test, one 400 m-long beetle bank sown with cock's-foot and Yorkshire fog *Holcus lanatus* (2.5 m wide, 0.5 m high) in an 18 ha field was compared with a 400 m-long hedge on the field edge (both habitats divided into 100 m blocks). In the second test, two 360 m-long beetle banks in an 8.6 ha field were divided into twenty 18 m-long blocks, sown with one of nine different grass treatments or left to naturally regenerate. In both tests invertebrates were collected from 11.5 cm diameter soil samples (3-10 samples/block). This study was part of the same experimental set-up as (*13*) and (*15*).

A replicated, randomized, controlled study in 1996-1997 in one field at the Michigan State University Entomology Farm, Michigan, USA (*6*) found that raised refuge strips did not affect the activity density of ground beetles (Carabidae) in surrounding cropped subplots in both years (numbers not provided). However raised refuge strips had seasonally higher ground beetle activity densities from May-August 1996 (average 4-16 beetles/trap) and May, July and August 1997 (2-6 beetles/trap) than surrounding crops (0.5-8 beetles/trap in 1996; 1-5 in 1997). There were eight 30 x 30 m plots, each divided into two 30 x 15 m subplots. Four pairs of subplots were separated by a 3.3 m-wide, 0.10 m-high refuge strip and four pairs had no refuge strip. The field was in a three-year crop rotation of soybean *Glycine max*, oats *Avena sativa* and maize *Zea mays*. The central 0.3 m section of refuge strips was planted with three perennial flowering plant species and a grass-legume seed mix was sown on either side of the flowering plants. Ground beetles were sampled in May-October in three pitfall traps/refuge strip or control area and six traps/subplot in the surrounding crop area.

A 2000 literature review (*7*) found two studies from the UK and USA showing natural enemy populations were larger in beetle banks than the surrounding crop (Rodenhouse *et al.* 1992) or other field margin habitats (*2*). There were fewer potato leafhoppers *Empoasca fabae* in fields with grass corridors (Rodenhouse *et al.* 1992). One study from 1988 (and updated in 1994) calculated that establishing a beetle bank in a 20 ha field could save £660 (US$1,090) if an aphid-induced yield loss of 5% was prevented and £300/year (US$495) in pesticide and labour costs if natural enemy populations kept aphid (Aphididae) numbers below a spray threshold (Wratten 1988, Wratten & van Emden 1995). Economic costs of establishing a beetle bank in a 20 ha field were approximately £85 (US$140) in year one based on: labour cost (1-2 days), yield loss from land taken out of production (assuming an average yield of 6 t/ha at £110/t, or US$180/t) and cost of grass seed (£5 or US$8). Gross yield lost in subsequent years because of the beetle bank taking up production land was calculated at £30 (US$50).

A literature review in 2000 (*8*) found one study in France (Fournier & Loreau 1999) that showed an increase in the diversity of ground beetles (Carabidae) when hedges were replanted. The effect was strongest near the hedge and declined with distance into the field.

A paired, replicated, controlled study in winters 1997-1998 and 1998-1999 and summer 1999 on five farms in the UK (*9*) found fewer rove beetles (Staphylinidae) on beetle banks (approximately 320-480 individuals/m^2) than in field margins (560-680 individuals) in both winters, however ground beetle (Carabidae) and spider (Araneae) numbers were similar between beetle banks (200-240 ground beetles/m^2 and 360-440 spiders/m^2) and field margins (200-280 ground beetles/m^2 and 400-500 spiders/m^2). Ground beetle and spider diversity was slightly higher in beetle banks than field margins and rove beetle diversity was higher in field margins. Of the other invertebrates sampled (not specifically listed as natural enemies or pests), soldier beetles (Cantharidae), typical bugs (Heteroptera), other Auchenorrhyncha (excluding leafhoppers (Cicadellidae), planthoppers (Delphacidae) and bugs (Hemiptera)), other spiders, small flies (Diptera) and ants (Formicidae) were significantly more abundant on field margins than beetle banks. Total invertebrate abundance was also higher on field margins than beetle banks (averaging 64.7 vs 46.7 invertebrates/sweep net). Predatory invertebrates were sampled on five beetle banks in winter 1997-1998 and 1998-1999. Other invertebrates were sampled on 22 beetle banks on five farms in summer 1999. Banks were paired with a neighbouring field margin. This study was part of the same experimental set-up as (*10*) and (*14*).

A replicated study in 1998 at two arable sites in Hampshire, UK (*10*) found that numbers of ground beetles (Carabidae) known to overwinter in boundary habitats were highest near beetle banks and declined further into the crop field in March. Beetles were more evenly spread across the field in the following months until June, when they were again clustered near the beetle bank. Ground beetles known to overwinter in the field were patchily distributed and concentrated towards the centre of the field. Beetle banks were studied in barley *Hordeum vulgare* and wheat *Triticum aestivum* fields. The study used 10 transects from the beetle bank into the field, with pitfall traps at 5, 25, 50, 75, 100 and 150 m from the beetle bank edge. The first site had 20 transects in two

fields either side of a single beetle bank and the second had 10 transects from a bank positioned along the edge of a single field. Ground beetles were categorized depending on whether they spend the winter in field boundaries or in the fields themselves. This study was part of the same experimental set-up as (*9*) and (*14*).

A replicated, controlled, randomized study in 1996 in a winter wheat *Triticum* sp. field in Leicestershire, UK (*11*) found significantly more cereal aphids *Sitobion avenae* 83 m away from a beetle bank than 8 m away during the peak infestation period. Aphid numbers were 34% higher at the peak infestation period when predators, including ground beetles (Carabidae), rove beetles (Staphylinidae), money spiders (Linyphiidae) and wolf spiders (Lycosidae), were excluded. Ground beetle species typical of open field habitats were most abundant near the beetle bank before the peak aphid infestation period, while species typical of boundary habitats were most abundant near the beetle bank in April, showing a slow movement from the bank into the crop. The 400 m long (2.5 m wide x 0.5 m high) beetle bank was established in 1992 in 7.48 ha of an 18.3 ha field. The field was divided into four 100 m blocks containing a control area, and a predator-exclusion area (both 7 x 8 m) at 8, 33, 58 and 83 m from the bank. Aphids were counted twice a week on 20 labelled wheat tillers in each area (2 July-16 August) and on 10 ears of wheat each week (25 July-19 August). Arthropod predators were also counted on the 10 ears of wheat, and in three pitfall traps/area once a week from April-July.

A 2002 review (*12*) of two reports (Wilson *et al*. 2000, ADAS 2001) evaluating the effects of the Pilot Arable Stewardship Scheme in two regions of the UK (East Anglia and the West Midlands) from 1998-2003 found that grass margin options (including beetle banks) benefitted bugs (Hemiptera) and sawflies (Symphyta) but not ground beetles (Carabidae). The review does not specify whether bugs and sawflies were natural enemies or pests. The grass margin set of options included sown grass margins, naturally regenerated margins, beetle banks and uncropped cultivated wildlife strips. The review does not distinguish between these. None of the beneficial effects were pronounced on beetle banks. The effects of the pilot scheme on invertebrates were monitored relative to control areas over three years. Grass margins were implemented on total areas of 361 and 294 ha in East Anglia and West Midlands respectively.

A study in 1995-1999 in arable land in Leicestershire, UK (*13*) found that spiders (Araneae) and some groups of bugs (Homoptera) were consistently more abundant in uncropped strips than in four crop types or in grazed pasture. Other bug groups (Heteroptera) were most abundant in uncropped strips in four out of five years. Abundance of other groups in different crop types varied between years. The experiment sampled insects from six habitats: wheat *Triticum aestivum*, barley *Hordeum vulgare*, oilseed rape *Brassica napus* and field bean *Vicia faba* crop fields, grazed pasture fields and uncropped strips. The uncropped strips included both beetle banks and strips sown with wild bird cover mix, and the study did not differentiate results from these two habitats. Insect sampling used a 'D-Vac' suction sampler. The study did not indicate whether insect groups were pests, natural enemies or neutral. This study was part of the same experimental set-up as (*5*) and (*15*).

A paired, replicated, controlled study on five arable estates in Hampshire and Wiltshire, UK (*14*) found that ground beetle (Carabidae) density and species diversity were higher on beetle banks than field margins in summer but not

winter. In spring and summer, ground beetle density and species diversity were higher in beetle banks (averaging 75 individuals/m^2 in spring, 90 individuals/m^2 in summer) than field margins (45 and 60 individuals, respectively). In winter there was no difference in ground beetle density (approximately 200-300 individuals/m^2), species richness (15-22 species) or diversity between beetle banks and field margins, but species richness increased with age in beetle banks. In summer, beetle banks had higher average cover of grass weeds but grass and broad-leaved weed cover was highly variable in both habitats. Ground beetles were surveyed on five beetle banks on one estate in January-February, May, August and February the following year. Vegetation was surveyed on 22 beetle banks (including those surveyed for beetles) on five estates in January-February (nine banks) and July (22 banks). Banks were 1-13 years old. Each bank was paired with a conventional permanent margin in the adjacent field. This study was part of the same experimental set-up as (*9*) and (*10*).

A replicated study in 1994-1998 assessing two beetle banks in arable land in Leicestershire, UK (*15*) found higher invertebrate predator densities in false oat grass *Arrhenatherum elatius* (2,045 individuals/m^2) than in red fescue *Festuca rubra* (1,492 individuals), crested dog's-tail *Cynosurus cristatus* (1,380 individuals) and naturally regenerated vegetation (1,060 individuals). Rove beetles (Staphylinidae), were the dominant predator family, and showed the same significant pattern (1,716 individuals/m^2 in false oat grass through to 834 individuals in naturally regenerated vegetation). Spider (Araneae) density was higher in cock's-foot (177 individuals/m^2) compared with red fescue (119 individuals) and naturally regenerated vegetation (107 individuals). Ground beetle (Carabidae) density was 2.5-3.5 times higher in cock's-foot than all other treatments. Boundary-type ground beetles dominated all treatments but were also more abundant in cock's-foot (328 individuals/m^2) compared with the other five treatments (69-126 individuals). Beetle banks created in spring 1993 were situated in an 8.6 ha clay soil field. Six treatments (five grass species and naturally regenerated vegetation) were established with two replicates/bank. Invertebrates were collected from soil samples gathered in January-February 1994-1997. Vegetation was examined visually and measured with a graduated board. This study was part of the same experimental set-up as (*5*) and (*13*).

A randomized, replicated study of a beetle bank over seven winters from early 1987 to early 1994 on a mixed arable estate in Hampshire, UK (*16*) found that ground beetle (Carabidae) and rove beetle (Staphylinidae) densities were often highest in blocks sown with cock's-foot *Dactylis glomerata* or Yorkshire fog *Holcus lanatus* (0.6-110.4 ground beetles/m^2, 1.2-125.4 rove beetles), although numbers were not always significantly higher than in creeping bent *Agrostis stolonifera* (3.1-15.4 ground beetles, 0.3-66.7 rove beetles) or perennial ryegrass *Lolium perenne* (2.1-11.5 ground beetles, 2.1-78.8 rove beetles). Densities of money spiders (Linyphiidae) and wolf spiders (Lycosidae) were also higher in cock's-foot and Yorkshire fog, although not always significantly. Ground beetle species composition changed from species typical of open fields to species of field boundaries over the study period. Field boundaries were sampled in the last three winters and had lower densities of predatory invertebrates than the beetle bank, but this was not tested statistically. One 290 m-long beetle bank was divided into six blocks into which eight sowing treatments/block were applied (this study examined only four single-species grass treatments). Predator

communities were sampled through ground zone searching and destructive sampling November-February. This study was part of the same experimental set-up as (*1*), (*2*), (*3*) and (*4*).

A replicated, controlled trial study in 2003-2004 at three organic mixed vegetable farms in British Columbia, Canada and Washington, USA and a series of replicated, controlled field cage experiments at a research station in Washington, USA (*17*) found fields with beetle banks had higher beetle (Coleoptera) activity densities than fields without banks (figures not given). However predation rates of housefly *Musca domestica* eggs were not associated with activity densities of either small beetles (< 1 cm long ground beetles (Carabidae) and rove beetles (Staphylinidae)) or the large ground beetle *Pterostichus melanarius*. Small beetle activity densities were reduced when *P. melanarius* individuals were added to 2 x 2 x 2 m caged areas of a radish *Rhaphanus sativus* field and the number of housefly eggs predated was significantly reduced. The number of housefly eggs predated was lower when alternative aphid (Aphididae) prey were present. Beetle banks 1.5 x 30-60 m (two banks 50 cm high, two field level) sown with orchardgrass *Dactylis glomerata* were established in April-June 2002. Five housefly eggs were placed on a 1 cm^2 peat block and covered with 0.5 cm soil at plant bases, five times/field.

A review (*18*) described one study ((*11*), above) which found that natural predators reduced aphid (Aphidoidea) numbers up to 58 m from a beetle bank, but with greatest reductions at 8 m from the bank. Another study (Thomas 1990) found reductions were highest on the beetle bank itself. Three studies ((*1*) and (*16*) above, and Collins *et* al. 2003) found between 18 and 2,180 natural predators/m^2 in beetle banks between 1987 and 1998, including 11-423 ground beetles (Carabidae), 1-1,550 rove beetles (Staphylinidae) and 6-470 spiders (Araneae)/m^2. Predator numbers on beetle banks (maintained for up to 10 years) were similar to or higher than numbers in field margins. Another study (Holland *et al.* 2004) found total numbers of predators varied from 1to 29 individuals/m^2 (in July and June respectively) in a cereal field without a beetle bank. In 2002 a beetle bank cost £975/ha to establish and £2/ha in income lost (with each subsequent crop) through land being occupied by the beetle bank (*11*).

(1) Thomas M.B. (1991) Manipulation of overwintering habitats for invertebrate predators on farmland. PhD thesis. University of Southampton.

(2) Thomas M.B., Wratten S.D. & Sotherton N.W. (1991) Creation of 'island' habitats in farmland to manipulate populations of beneficial arthropods: predator densities and emigration. *Journal of Applied Ecology*, 28, 906-917.

(3) Thomas M.B., Wratten S.D. & Sotherton N.W. (1992) Creation of 'island' habitats in farmland to manipulate populations of beneficial arthropods: predator densities and species composition. *Journal of Applied Ecology*, 29, 524-531.

(4) MacLeod A. (1994) Provision of plant resources for beneficial arthropods in arable ecosystems. PhD thesis. University of Southampton.

(5) Collins K.L., Wilcox A., Chaney K. & Boatman N.D. (1996) Relationships between polyphagous predator density and overwintering habitat within arable field margins and beetle banks. *Proceedings of the British Crop Protection Conference: Pests and Diseases*. Farnham, UK, pp 635-640.

(6) Carmona D.M. & Landis D.A. (1999) Influence of refuge habitats and cover crops on seasonal activity-density of ground beetles (Coleoptera: Carabidae) in field crops. *Environmental Entomology*, 28, 1145-1153.

(7) Dent D. (2000) Biological control. Pages 180-234 in: D. Dent (ed) *Insect pest management*, CABI Publishing, Wallingford, UK.

(8) Holland J.M. & Luff M.L. (2000) The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated Pest Management Reviews*, 5, 109-129.
(9) Thomas S.R., Goulson D. & Holland J.M. (2000) The contribution of beetle banks to farmland biodiversity. *Aspects of Applied Biology*, 62, 31-38.
(10) Thomas S.R. (2001) Assessing the value of beetle banks for enhancing farmland biodiversity. PhD thesis. University of Southampton.
(11) Collins K.L., Boatman N.D., Wilcox A., Holland J.M. & Chaney K. (2002) Influence of beetle banks on cereal aphid predation in winter wheat. *Agriculture, Ecosystems & Environment*, 93, 337-350.
(12) Evans A.D., Armstrong-Brown S. & Grice P.V. (2002) The role of research and development in the evolution of a 'smart' agri-environment scheme. *Aspects of Applied Biology*, 67, 253-264.
(13) Moreby S.J. & Southway S. (2002) Cropping and year effects on the availability of invertebrate groups important in the diet of nestling farmland birds. *Aspects of Applied Biology*, 67, 107-112.
(14) Thomas S.R. (2002) The refuge role of beetle-banks and field margins for carabid beetles on UK arable farmland: densities, composition and relationships with vegetation. *Proceedings of the 'How to Protect or What We Know About Carabid Beetles: from Knowledge to Application, from Wijster (1969) to Tuczno (2001)' 2002 Conference*. Warsaw, Poland, pp 185-199.
(15) Collins K.L., Boatman N.D., Wilcox A. & Holland J.M. (2003) Effects of different grass treatments used to create overwintering habitat for predatory arthropods on arable farmland. *Agriculture, Ecosystems and Environment*, 96, 59-67.
(16) MacLeod A., Wratten S.D., Sotherton N.W. & Thomas M.B. (2004) 'Beetle banks' as refuges for beneficial arthropods in farmland: long-term changes in predator communities and habitat. *Agricultural and Forest Entomology*, 6, 147-154.
(17) Prasad R.P. & Snyder W.E. (2006) Polyphagy complicates conservation biological control that targets generalist predators. *Journal of Applied Ecology*, 43, 343-352.
(18) Tillman P.G., Smith H.A. & Holland J.M. (2012) Cover crops and related methods for enhancing agricultural biodiversity and conservation biocontrol: successful case studies. Pages 309-327 in: G. M. Gurr, S. D. Wratten & W. E. Snyder (eds) *Biodiversity and Insect Pests: Key Issues for Sustainable Management*, Wiley-Blackwell, Oxford, UK.

Additional references

Wratten S.D. (1988) The role of field boundaries as reservoirs of beneficial insects. Pages 144-150 in: A.J. Burn, T.H. Coaker & P.C. Jepson (eds.) *Environmental Management in Agriculture: European Perspectives*. EEC/Pinter Publishers, London.
Thomas M.B. (1990) The role of man-made grassy habitats in enhancing carabid populations in arable land. Pages 77-85 in: N.E. Stork (ed.) *The Role of Ground Beetles in Ecological and Environmental Studies*, Intercept Ltd., Andover, UK.
Rodenhouse N.L., Barrett G.W., Zimmerman D.M. & Kemp J.C. (1992) Effects of uncultivated corridors on arthropod abundances and crop yields in soybean agroecosystems. *Agriculture, Ecosystems and Environment*, 38, 179-191.
Wratten S.D. & van Emden H.F. (1995) Habitat management for enhanced activity of natural enemies of pests. Pages 117-145 in: D.M. Glen, M.P. Greaves & H.M. Anderson (eds.) *Proceedings of the 13th Long Ashton Symposium, England: Ecology and Integrated Farming Systems*. John Wiley & Sons, London.
Fournier E. and Loreau M. (1999) Effects of newly planted hedges on ground-beetle diversity (Coleoptera, Carabidae) in an agricultural landscape. *Ecography* 22, 87–97.
Wilson S., Baylis M., Sherrott A. & Howe G. (2000) *Arable Stewardship Project Officer Review*. F. a. R. C. Agency report.
ADAS (2001) *Ecological evaluation of the Arable Stewardship Pilot Scheme, 1998-2000*. ADAS report.
Collins K.L., Boatman N.D., Wilcox A.W. & Holland J.M. (2003) A 5-year comparison of overwintering polyphagous predator densities within a beetle bank and two conventional hedgebanks. *Annals of Applied Biology*, 143, 63-71.
Holland J.M., Winder L., Woolley C., Alexander C.J. & Perry J.N. (2004) The spatial dynamics of crop and ground active predatory arthropods and their aphid prey in winter wheat. *Bullentin of Entomological Research*, 94, 419-431.

4.2. Use crop rotation in potato farming systems

- **Pests:** Nine studies from Canada and the USA and one review investigated the effect of crop rotation on pest or pathogen populations in potato. Three studies[1,7,8] (including two replicated studies of which one randomized and one controlled) and a review[4] found crop rotation reduced pest populations and crop diseases in at least one year or at least one site. One paired study[2] found pest populations increased in crop rotation. Four studies[3,5,9,10] (including one replicated, randomized, controlled trial) found increases and decreases in pest populations depending on rotation crops used and other treatments. One replicated, randomized, controlled study[6] found no effect.
- **Yield:** Three[6,7,10] out of five studies (all replicated, controlled, two also randomized) from Canada and the USA, found that crop rotation increased crop yield in some years or with certain rotation crops. The two other studies[3,9] (both replicated, one also randomized and one replicated) found yield increases and decreases depending on rotation crops used.
- **Profit:** One replicated, controlled study[7] found that crop rotation increased profit.
- **Insecticides:** Two studies[1,7] (one replicated, controlled) found that fewer insecticide treatments were needed on rotated plots.
- **Crops studied** were alfalfa[6,8], barley[2,3,8], broccoli[5], brown mustard[10], buckwheat[5], cotton[7], lupins[5], maize[6,10], oats[4,5,10], pearl millet[9,10], peas[5], potato[1,2,3,4,5,6,7,8,9,10], rye[1,4,6,9,10], sorghum[6], soybean[3,7,8,10], sugar beet[4], timothy grass[8], wheat[3,7] and yellow sweet clover[6].

Background

Crop rotation involves alternating between two or more commercial arable crops in successive growing seasons. It may also include ley or fallow periods, as long as at least two crops are involved. Growing different crops each year may help avoid the build-up of crop-specific pests and pathogens.

The studies presented for this synopsis are only those that test rotations including potato *Solanum tuberosum*. We have found approximately 200 further studies on crop rotation in other crop types which will be summarized in the future. Here we present evidence from 10 of 32 studies testing this action for potatoes.

A paired sites study in 1982-1983 on Long Island, New York, USA (*1*) found that on five of seven pairs of sites, density of early season adult Colorado potato beetles *Leptinotarsa decemlineata* (pest) was reduced by 95.8% in 1982 and by 69.5% in 1983 in fields that were rotated to rye *Secale cereale* in the previous year, compared to fields that had been planted with potatoes *Solanum tuberosum* for two consecutive years. In the other two pairs of sites, potato beetle numbers were low in both rotated and non-rotated fields. Under an integrated pest management scheme, non-rotated fields required an average of one additional insecticide spray over the growing season, and in three pairs of fields crop damage was significantly lower in the rotated field. The experiment used pairs of rotated and non-rotated fields on four farms in 1982 and five in 1983. Fields averaged 8 ha in size and were up to 2 km apart. Colorado potato beetle densities were monitored weekly from late May. Densities were estimated by counting beetles on 80 potato stalks in 1982 and 50 stalks in 1983.

A paired sites study in 1982-1983 on Long Island, New York, USA (*2*) found that potatoes *Solanum tuberosum* in fields that had been rotated to barley *Hordeum vulgare* the previous season had 1.6 times more lesion nematodes *Pratylenchus* spp. (pest) per gram of root as fields that had grown potatoes in both seasons (395 nematodes/g potato root vs 251 for non-rotated fields). Nematode soil populations were 1.4 times higher in rotated fields (376 nematodes/100 cm^3 vs 274 for unrotated fields). Data from the same experiment on Colorado potato beetle *Leptinotarsa decemlineata* numbers is described in Wright 1984 (*1*). The experiment used pairs of rotated and non-rotated fields on four farms in 1982 and five in 1983. Fields averaged 8 ha in size and were up to 2 km apart.

A randomized, replicated study in 1983-1987 on Prince Edward Island, Canada (*3*) found more root lesion nematodes *Pratylenchus penetrans* (pest) in barley *Hordeum vulgare* after one year of soybean *Glycine max* (3,240 nematodes/g root and 4,170 nematodes/kg soil) than after potato *Solanum tuberosum*, wheat *Triticum aestivum*, or two years of continuous barley (630-780 nematodes/g root and 1,260-1,700 nematodes/kg soil). Barley yields were highest after potato (3,514 kg/ha), followed by soybean (3,293 kg/ha), wheat (3,195 kg/ha) and continuous barley (2,712 kg/ha). In soybean after barley, nematode density and yield did not change according to crops two years before. In the final study year, nematode density did not vary between plots, but potato yield was lower in plots that had grown potato or soybean three years before. Crops were grown in randomized 10 x 32 m plots, in a field planted with barley the previous year. Each rotation pattern was replicated six times. Plots grew barley, wheat, soybean or potato in 1984, barley or potato in 1985, soybean in 1986 and potato in 1987. Seeding rates, fertilizer, pesticide and herbicide use followed standard practice for the region.

A 1992 review (*4*) on plant-parasitic nematodes (Nematoda) found that crop rotations with low proportions of nematode host plants generally prevented nematode (pest) population build-up in soils. No sugar beet cyst nematodes *Heterodera schachtii* were found in a rotation where sugar beet *Beta vulgaris* was grown for one year out of six with other rotation crops that were non-hosts, but nematodes were found when sugar beet was grown at a higher frequency. No potato cyst nematodes *Globodera rostochiensis* were found in a five year rotation with one year of potato *Solanum tuberosum* followed by four years of non-host crops, but the nematode was present with two years of potato and present with increasing population density with three years of potato in every five. Population densities of cereal cyst nematode *Heterodera avenae* were low in rotations with 25 or 50% oats *Avena sativa* or rye *Secale cereale* (0-58 eggs and larvae/100 cm^3 soil) but generally higher with 75% (9-280 eggs and larvae) or 100% oats or rye (29-920 eggs and larvae) although populations remained low at some sites growing rye. The review covered 23 studies, mostly from Eastern Europe.

A study in 1987-1990 in arable land in Presque Isle, Maine, USA (*5*) found that under moldboard ploughing, incidence of *Rhizoctonia solani* disease in potatoes *Solanum tuberosum* was 91% higher than average in rotation with oats *Avena sativa*, but did not vary with four other rotation crops: buckwheat *Fagopyrum esculentum*, lupins *Lupinus albus*, peas *Pisum sativum* and broccoli *Brassica oleracea*. Under chisel ploughing, *R. solani was* 83% lower than average in rotation with broccoli but was not affected by rotation with oats, buckwheat,

lupin or peas. No differences between rotation crops were observed until the fourth year of the study. Rotation crop showed no effect on *R. solani* soil populations. The five rotation crops were planted in two year rotations with Russet Burbank potatoes. Rotation plots were 8.6 x 20.1 m, with 4.3 x 20.1 m subplots under each ploughing treatment. All rotation crops were harvested except buckwheat, which was ploughed in as a green manure. Ten weeks after planting, 10 plants from each potato plot were scored for *R. solani* incidence and twenty-five 20 cm deep soil samples were taken to assess soil populations.

A randomized, replicated, controlled study in 1989-1991 in Michigan, USA (*6*) found that potato *Solanum tuberosum* yield was significantly higher in fields that had grown alfalfa *Medicago sativa* (32.3 t/ha) or yellow sweet clover *Melilotus officinalis* (33.8 t/ha) in the previous two years than fields that had grown potatoes for three years continuously (22.8 t/ha). Yield of potato in rotation with one year of rye *Secale cereale*, one or two years of maize *Zea mays* and one or two years of a sorghum hybrid *Sorghum halepense x sudanense* was not significantly different to continuous potato. Populations of wilt fungus *Verticillium dahliae* and root lesion nematode *Pratylenchus penetrans* were not affected by crop rotations. The experiment used five replicates of ten rotation treatments. Plots were 15 m long and four crop-rows wide. Crop management followed local recommendations for conventional potato production. Wilt fungus and root lesion nematode were sampled at the beginning, middle and end of each growing season using eight to twelve 600 cm^3 soil cores in each plot.

A replicated, controlled study in 1994-1996 in Virginia, USA (*7*) found that potatoes *Solanum tuberosum* grown in 1995 in plots rotated with wheat *Triticum* sp. or double-cropped wheat and soybean *Glycine max* in 1994 had lower Colorado potato beetle *Leptinotarsa decemlineata* (pest) populations and 47% higher yields in 1995 (22.52 vs 15.34 t/ha) than plots where potatoes were grown in 1994. In 1996, Colorado potato beetle populations were much smaller and not significantly different between plots rotated with cotton *Gossypium* spp. or left fallow and non-rotated plots. In both years, more insecticide sprays were required in non-rotated plots, and in 1995 rotated plots had a return of US$2,342.50/ha compared to US$552.50/ha for non-rotated plots. The experiment used 7.6 m long, three row wide plots in 1994-1995 and 6.1 m long, four row wide plots in 1995-1996. In 1994 rotation crops were wheat or wheat-soybean double crop, and in 1995 rotation crops were cotton or fallow. Unrotated control plots were replicated four times, whilst each rotated plot was replicated twice. Rotated and non-rotated plots were a minimum of 150 m apart. Insecticides were applied based on threshold beetle numbers.

A randomized, replicated study in 1999-2003 in Maine, USA (*8*) found that numbers of Colorado potato beetle *Leptinotarsa decemlineata* larvae were not significantly different between a two-year rotation (potato *Solanum tuberosum*-barley *Hordeum vulgare*), an intensive four-year rotation (potato-soybean *Glycine max*-potato-barley) and an integrated four-year rotation (potato-soybean-barley-alfalfa *Medicago sativa*/timothy *Phleum pratense*) except in the final year of the experiment when the two-year rotation had significantly more large larvae (1.72 larvae/plant), compared to the integrated four-year rotation (1.51) and the intensive four-year rotation (1.45). The experiment used 96 plots, each 41 x 14.6 m, split into four blocks. Rotation treatments were randomized within each block. Imidacloprid was used for pest control on all plots as part of

an integrated system, with thresholds for spraying of one adult, eight small larvae or three large larvae/plant.

A replicated, controlled trial in 2001-2002 at L'Assomption, Quebec, Canada (*9*) found that density of root lesion nematode *Pratylenchus penetrans* (pest) was significantly higher after rotation of potatoes *Solanum tuberosum* with rye *Secale cereale* (8533 nematodes/kg soil) than after rotation with grain pearl millet *Pennisetum glaucum* (867 nematodes/kg soil) or continuous potato cultivar Superior (467 nematodes/kg soil). In the following growing season yields of potato cultivar Superior were lower in rye plots (10.8 tons/ha) than in grain pearl millet plots (24.1 tons/ha) or in continuous potato plots (21.8 tons/ha). Yields of potato cultivar Hilite Russet varied less between rotation crops. The experiment was carried out in four plots that had all grown potatoes in 2000. Each plot had one strip of each treatment. Strips were 10 x 80 m. Grain pearl millet was sown at 5.8 kg/ha with 230 kg/ha N in the form of 19-19-19 NPK fertilizer. Rye was sown at 120 kg/ha and potato planted at 2,313 kg/ha. In 2002 half of each strip was planted with each of the two potato varieties and yield was recorded. Nematodes were monitored twice each year using twelve 20 cm deep soil cores/strip.

A randomized, replicated, controlled study in 1998-2003 in arable land in Quebec, Canada (*10*) found that population density of root lesion nematodes *Pratylenchus penetrans* (pest) was consistently low in autumn following forage pearl millet *Pennisetum glaucum* cultivar CFPM 101 (11-430 nematodes/kg soil) and generally low following grain pearl millet *Pennisetum glaucum* cultivar CGPM H-1 (94-2,297 nematodes/kg soil) compared with other crops. Nematode population densities tended to be high in autumn after brown mustard *Brassica juncea* (1,800-5,735 nematodes/kg soil), maize *Zea mays* (2,043-2,467), oats *Avena sativa* (3,997-6,353), potato *Solanum tuberosum* (3,257-6,365), rye *Secale cereale* (3,753-9,728) and soybean *Glycine max* (1,398-4,768). After soybean nematode population densities were low the following spring (73-300/kg soil), whereas for after other crops they remained high. Marketable potato yield in the fourth year of the experiment was highest after three year rotations ending in forage or grain pearl millet (38.4-55.9 t/ha) and lower with other final rotation crops (23.5-43.0 t/ha). The study had 14 different three year rotation treatments, each of which was applied at random to eight replicate 1 x 2 m plots. In the fourth year, potatoes were grown in all plots. Fertilizers, pesticides and irrigation followed local standard practice and weeds were removed by hand.

(1) Wright R.J. (1984) Evaluation of crop rotation for control of Colorado potato beetles (Coleoptera: Chrysomelidae) in commercial potato fields on Long Island. *Journal of Economic Entomology*, 77, 1254-1259.

(2) Leach S.S., Fry W.E., Jones R.T., Loria R., Storch R.H., Sweet R.D.*, et al.* (1986) *Integrated systems for managing potatoes in the Northeast.* Agricultural Experiment Station University of Maine Technical Bulletin 116.

(3) Kimpinski J., Edwards L.M., Gallant C.E., Johnson H.W., MacLeod J.A. & Sanderson J.B. (1992) Influence of previous crops and nematicide treatments on root lesion nematode populations and crop yields. *Phytoprotection*, 73, 3-11.

(4) Wolny S. (1992) The threat of parasitic nematodes to farm crops grown in various rotations and monoculture. *Acta Academiae Agriculturae ac Technicae Olstenensis, Agricultura*, 103-113.

(5) Leach S.S., Porter G.A., Rourke R.V. & Clapham W.M. (1993) Effects of moldboard plowing, chisel plowing and rotation crops on the rhizoctonia disease of white potato. *American Potato Journal*, 70, 329-337.

(6) Chen J., Bird G.W. & Mather R.L. (1995) Impact of multi-year cropping regimes on *Solanum tuberosum* tuber yields in the presence of *Pratylenchus penetrans* and *Verticillium dahliae*. *Journal of Nematology*, 27, 654-660.
(7) Speese J. & Sterett S.B. (1998) Crop rotation reduces the cost of Colorado potato beetle control in potatoes. *HortTechnology*, 8, 229-234.
(8) Alyokhin A., Porter G., Groden E. & Drummond F. (2005) Colorado potato beetle response to soil amendments: a case in support of the mineral balance hypothesis? *Agriculture, Ecosystems & Environment*, 109, 234-244.
(9) Dauphinais N., Belair G., Fournier Y. & Dangi O.P. (2005) Effect of crop rotation with grain pearl millet on *Pratylenchus penetrans* and subsequent potato yields in Quebec. *Phytoprotection*, 86, 195-199.
(10) Belair G., Dauphinais N., Fournier Y., Dangi O.P. & Ciotola M. (2006) Effect of 3-year rotation sequences and pearl millet on population densities of *Pratylenchus penetrans* and subsequent potato yield. *Canadian Journal of Plant Pathology*, 28, 230-235.

4.3. Combine trap and repellent crops in a push-pull system

- **Parasitism:** Two[1,8] randomized, replicated, controlled studies from Kenya found that push-pull cropping systems increased parasitism of stem borer larvae. One[8] of the studies found no effect on egg parasitism.
- **Natural enemies:** Two[2,8] randomized, replicated, controlled studies from Kenya and South Africa found push-pull systems had more natural predators, both in overall totals and the abundance of different predator groups.
- **Pests:** Two[1,3] of three studies (two randomized, replicated, controlled) in Ethiopia, Kenya and South Africa found fewer pests. One study[9] found no effect on pest infestation, but pests were scarce throughout. Two replicated, controlled studies[4,7] (one also randomized) found fewer witchweeds.
- **Crop damage:** Two[4,7] of three replicated, controlled studies (one also randomized) found less pest damage, but one study[9] (where pest numbers were low) found effects varied between years and types of damage symptom.
- **Yield:** Four[1,4,5,7] of five replicated, controlled studies (two also randomized) found higher yields and one[9] found no effect.
- **Profit and cost:** Two studies[5,7] in Kenya and a review[10] found greater economic benefits. One study[5] found higher production costs in the first year, but equal or lower costs in the following five years.
- **Crops studied** were maize[1,2,3,4,5,6,7,8,9,10] and beans[5,7].

Background

Push-pull systems involve intercropping the main crop with plants that are repellent to pests (the 'push') while also growing plants (trap crops) that are attractive to pests around the main crop (the 'pull'). This combination of repellent and attractive companion plants keeps invertebrate pests away from the crop and may provide additional benefits through improved habitat and resources for natural enemies. Push-pull systems can also be designed to suppress weeds at the same time as controlling pests. Ground-dwelling invertebrates are frequently surveyed using pitfall traps – small pots buried in

the ground up to their rim and left empty or filled with liquid preservatives or water.

Here we present evidence from 10 of 13 studies testing this action.

A replicated, paired, controlled study in 1998-1999 in western Kenya (*1*) found greater parasitism of stem borer (Crambidae and Noctuidae) larvae by wasps *Cotesia* spp. in a push-pull maize *Zea mays* system than in maize monoculture. On average, 12-43% of larvae were parasitized in a maize, Napier grass *Pennisetum purpureum* (trap crop) and desmodium *Desmodium* spp. (repellent crop) push-pull system (compared with 5-26% in a monoculture control) and 56-78% were parasitized in a maize, Napier grass and molasses grass *Melinis minutiflora* push-pull system (23-34% in controls). Fewer stem borers occurred in the push-pull systems, with 8-20 stem borers/40 maize plants in the maize-Napier-desmodium system vs 39-57 stem borers in controls, and 8-10 stem borers in the maize-Napier-molasses system vs 40-42 stem borers in controls. Maize yields were higher in the maize-Napier-desmodium (4-7 t/ha) and maize-Napier-molasses (7 t/ha) push-pull systems than controls (2-5 t/ha). Two push-pull systems were tested on 10 farms over two districts and two years. Napier grass was planted in 1 m-wide margins around 900 m^2 maize plots in both systems. In the first system maize and desmodium were planted in alternate rows. In the second system one row of molasses grass was planted for every 10 maize rows. A control was placed 15 m from each push-pull treatment.

A randomized, replicated, controlled study in 2001-2002 in western Kenya (*2*) found more natural predators in push-pull maize *Zea mays* systems than in maize monocultures at three sites and in all maize growth stages. More predatory ants (Formicidae) occurred in push-pull than control plots (averaging 38-73 vs 22-28 ants/maize growth stage in 2001, 38-109 vs 23-59 ants in 2002) in all maize growth stages. More spiders (Araneae) occurred in push-pull than control plots in all stages in 2001 (14-35 vs 10-20 spiders) and in the early and flowering (but not mature) stages in 2002 (11-30 vs 7-13 spiders). More earwigs (Dermaptera) occurred in push-pull than control plots during the early (pre-flowering) stage (16 vs 7 earwigs) but populations were similar or showed inconsistent differences in other stages. Two important predators of pest stem borers (Lepidoptera), including a ladybird *Cheilomenes* sp. and a lacewing *Chrysopa* sp., were only found in push-pull plots. Push-pull systems were tested in two long rainy seasons and comprised maize with a Napier grass *Pennisetum purpureum* or Sudan grass *Sorghum vulgare sudanese* trap crop and a silverleaf desmodium *Desmodium uncinatum* repellent crop. Fields were 30 x 30, 40 x 40 or 50 x 50 m.

A randomized, controlled trial in 2002-2003 in Potchefstroom, South Africa (*3*) found fewer pest spotted maize beetles *Astylus atromaculatus* in push-pull cropping systems of maize *Zea mays*, silverleaf desmodium *Desmodium uncinatum* and Napier grass *Pennisetum purpureum* (45-252 spotted maize beetles/plot) than in maize monocultures (453-649 beetles). The same effect occurred with *Bacillus thuringiensis* maize or conventional maize varieties. A greenhouse study found fewer spotted maize beetle catches in baited traps containing silverleaf desmodium (12% of captures) than baited control traps (27%), although similar tests in sorghum *Sorghum bicolor* fields found no effect of desmodium on beetle captures. Two push-pull plots (with different maize varieties) were compared with two monoculture controls. Push-pull plots

comprised silverleaf desmodium planted between maize rows and Napier grass along plot margins. Plots were 38 x 35 m. Spotted maize beetles were counted on every maize plant in six 5 x 5 m areas/plot. In the greenhouse study, yellow water traps containing 2-phenylethanol lures were placed in cages with either a potted desmodium plant or a pot without desmodium. One hundred beetles were released in each cage and captures were monitored after 24 hours.

A replicated, controlled trial in 2003-2006 in 14 districts in western Kenya (*4*) found 70-95% fewer purple witchweeds *Striga hermonthica* in a push-pull maize *Zea mays* cropping system (averaging 88 purple witchweeds/100 maize plants) than in maize monoculture (549 purple witchweeds), at 10 weeks after planting. Fewer maize plants were affected by stem borer (mainly maize stalk borer *Busseola fusca* and spotted borer *Chilo partellus*) damage in the push-pull system (averaging 6% of plants damaged) than in maize monoculture (23%). Maize yields were 37-129% higher in the push-pull (averaging 4.1 t/ha) than the monoculture system (2.2 t/ha) for all districts and seasons. In each district, the experiment took place on 20 randomly selected farms and for 3-7 cropping seasons. One push-pull and one monoculture plot was established on each farm. The push-pull system comprised silverleaf desmodium *Desmodium uncinatum* planted between maize rows, with three rows of Napier grass *Pennisetum purpureum* planted around the plot. The innermost row of Napier grass was planted 1 m from the maize crop. Stem borer damage was assessed for 100 maize plants/plot and purple witchweeds were counted in a 15 cm radius around each maize plant.

A replicated, controlled study in 1998-2004 in six districts in western Kenya (*5*) found higher maize *Zea mays* yields in a push-pull cropping system (averaging 1.9-6.3 t/ha) than in maize-bean *Phaseolus* sp. intercrop (0.9-3.9 t/ha) or maize monoculture (1.0-3.9 t/ha) systems. Economic benefits were also higher in the push-pull system (averaging a US$47-880/ha gain) than in maize-bean (US$-25/ha loss to a US$491/ha gain) or maize monoculture (US$-113/ha loss to a US$156/ha gain) systems, in all but one district in one year. Total production costs were typically higher in the push-pull (US$236-394/ha) than the maize-bean (US$198-344/ha) or maize monoculture (US$172-266/ha) systems in the first study year at each site. Push-pull system costs (US$200-357/ha) were equal to or lower than costs in the maize-bean (US$221-332/ha) or monoculture (US$183-293/ha) systems in subsequent years. The push-pull system (designed to control stem borers (Lepidoptera) and weeds *Striga* spp.) comprised alternate rows of maize and silverleaf desmodium *Desmodium uncinatum*, with three rows of Napier grass *Pennisetum purpureum* planted around plots. Controls were intercropped maize and beans and monocropped maize. Ten farmers in each district implemented the three treatments on 600-2,225 m^2 plots. Yields were measured at harvest.

A randomized, replicated, controlled study in the 2002-2004 at three sites (*6*) found more wolf spiders (Lycosidae) in push-pull maize *Zea mays* cropping systems than in maize monoculture in western Kenya (averaging 31-141 vs 19-71 wolf spiders/plot) and Potchefstroom, South Africa (15-16 vs 6 wolf spiders). Overall spider numbers (Araneae) were also higher in push-pull than monoculture systems in Kenya (52-187 vs 30-101 spiders/plot) and South Africa (21-28 vs 9-11 spiders). Spider diversity was similar between cropping systems in Kenya (21-60 species/plot) but higher in push-pull than monoculture systems

in South Africa (21-31 vs 9-14 species). Wolf spider diversity was similar between systems at all sites. Each cropping system was replicated four times at two sites in Kenya (using 40 x 40 m plots) and one site in South Africa (35 x 38 m plots). The push-pull system comprised silverleaf desmodium *Desmodium uncinatum* grown between maize rows and Napier grass *Pennisetum purpureum* planted around the plots. Spiders were sampled by pitfall traps and soil samples. Five pitfalls were placed in four 15 x 15 m areas/plot and monitored weekly. Five soil samples/plot (20 x 20 x 20 cm) were taken fortnightly.

A randomized, replicated, controlled study in three seasons between 2007 and 2008 in western Kenya (*7*) found fewer purple witchweeds *Striga hermonthica* in push-pull cropping systems (1-27 plants/plot) than in control plots of intercropped maize *Zea mays* and beans *Phaseolus vulgaris* (139-269 plants) or maize monoculture (259-460 plants), 12 weeks after planting. Damage to maize plants by cereal stem borers (Lepidoptera) was lower in push-pull cropping systems (0.4-6.7% plants damaged/plot) than in maize-bean intercrop (11-18% plants) and maize monoculture (10-28%) controls at 12 weeks after planting. Maize yields were higher in push-pull systems (4.6-5.6 t/ha) than intercropped (2.6-3.1 t/ha) and monoculture (2.8-3.5 t/ha) controls. Economic benefits were also greater in the push-pull system (US$639-1,532/ha) than in intercropped (US$45-129/ha) and monoculture controls (US$-176/ha loss to a US$91/ha gain). Push-pull systems of maize and beans provided similar weed and stem borer control, as well as similar yields and benefits, to push-pull systems of maize only. The push-pull systems comprised silverleaf desmodium *Desmodium uncinatum* grown between rows of maize or rows of mixed maize and beans. Three rows of Napier grass *Pennisetum purpureum* were planted around the plots. Treatments were replicated four times at two sites in 6 x 6 m plots.

A randomized, replicated, controlled study in 2002-2003 at two sites in western Kenya (*8*) found proportionately greater parasitism of young stem borers (Lepidoptera) in a push-pull cropping system (19% of larvae and pupae parasitized/plot) than in maize *Zea mays* monoculture (9-11% parasitized). Mortality caused by other factors (such a microbial disease) was similar between the push-pull system (range of 13.0-15.2% larvae and pupae killed) and the monoculture (9.6-11.4%). Similar proportions of stem borer eggs were parasitized in the push-pull and monoculture systems (21 vs 18-25% eggs parasitized). Push-pull and monoculture treatments were tested in 40 x 40 m plots. Push-pull plots contained silverleaf desmodium *Desmodium uncinatum* between rows of maize and Napier grass *Pennisetum purpureum* trap crops around plot margins (spaced 1 m from the crop). Treatments were replicated four times at each site. Stem borer eggs, larvae and pupae were sampled from 10 maize plants in each of four 15 x 15 m areas/plot. Samples were assessed for parasitism by parasitoid wasps (Hymenoptera) in a laboratory. A separate laboratory study found that the common parasitoid wasp *Cotesia sesamiae* was attracted to silverleaf desmodium flowers.

A replicated, controlled study in 2004-2005 in Sibu-Sire, Ethiopia (*9*) found similar stem borer infestation in maize *Zea mays* grown in a push-pull system (averaging 10-14% plants infested) and a monoculture control (10-19%) at harvest. Stem borer (Noctuidae and Crambidae) larvae densities were low, but fewer occurred in the push-pull system (0.05 borers/plants) than control (0.18 borers/plant) in 2005. Numbers were similar between treatments (0.3-0.4

borers/plant) in 2004. Cob damage was also similar between push-pull (0.3-0.7% cob surface damaged) and control (0.4-0.8%) systems in both years. Stem tunnelling by stem borers was scarcer in the push-pull (0.8%) than control (1.9%) system in 2005, but similar in 2004 (0.3 vs 0.5%). Yield was similar between the push-pull (2.4-3.3 t/ha) and control (2.0-4.6 t/ha) systems in both years. The push-pull system used greenleaf desmodium *Desmodium intortum* between maize rows and three rows of Napier grass *Pennisetum purpureum* (of 50 cm width) along plot margins. The control comprised maize only. The push-pull system and control were tested at seven sites (0.5 ha) in 0.25 ha plots each. Infestation and yield were measured in four 4 x 4 m areas/plot, damage was assessed for 20 randomly selected plants.

A review in 2010 (*10*) described two studies that found significant control of stem borers (Lepidoptera) and purple witchweed *Striga hermonthica* when maize *Zea mays* was grown in a pull-pull system (Khan *et al.* 2000, the same study as (*1*) and (*4*)). Napier grass *Pennisetum purpureum* margins acted as a trap crop for stem borers and greenleaf desmodium *Desmodium intortum* or silverleaf desmodium *Desmodium uncinatum* intercrops acted as weed- and pest-repellent plants. One study (*4*) found that the push-pull system improved maize yields by approximately 2 t/ha/season compared to maize monocultures. The push-pull system also provided higher monetary benefits than maize monocultures ((*5*) and De Groote *et al*. 2008).

(1) Khan Z.R., Pickett J.A., Wadhams L. & Muyekho F. (2001) Habitat management strategies for the control of cereal stemborers and striga in maize in Kenya. *Insect Science and its Application*, 21, 375-380.
(2) Midega C.A.O. & Khan Z.R. (2003) Impact of a habitat management system on diversity and abundance of maize stemborer predators in Western Kenya. *Insect Science and its Application*, 23, 301-308.
(3) Midega A.O., Van den Berg J. & Khan Z.R. (2007) Habitat management in control of *Astylus atromaculatus* (Coleoptera: Melyridae) in maize under subsistence farming conditions in South Africa. *South African Journal of Plant and Soil*, 24, 188-191.
(4) Khan Z.R., Midega C.A.O., Amudavi D.M., Hassanali A. & Pickett J.A. (2008) On-farm evaluation of the 'push-pull' technology for the control of stemborers and striga weed on maize in western Kenya. *Field Crops Research*, 106, 224-233.
(5) Khan Z.R., Midega C.A.O., Njuguna E.M., Amudavi D.M., Wanyama J.M. & Pickett J.A. (2008) Economic performance of the 'push-pull' technology for stemborer and *Striga* control in smallholder farming systems in western Kenya. *Crop Protection*, 27, 1084-1097.
(6) Midega C.A.O., Khan Z.R., Van den Berg J., Ogol C., Dippenaar-Schoeman A.S., Pickett J.A.*, et al.* (2008) Response of ground-dwelling arthropods to a 'push-pull' habitat management system: spiders as an indicator group. *Journal of Applied Entomology*, 132, 248-254.
(7) Khan Z.R., Midega C.A.O., Wanyama J.M., Amudavi D.M., Hassanali A., Pittchar J.*, et al.* (2009) Integration of edible beans (*Phaseolus vulgaris* L.) into the push-pull technology developed for stemborer and *Striga* control in maize-based cropping systems. *Crop Protection*, 28, 997-1006.
(8) Midega C.A.O., Khan Z.R., Van den Berg J., Ogol C.K.P.O., Bruce T.J. & Pickett J.A. (2009) Non-target effects of the 'push-pull' habitat management strategy: parasitoid activity and soil fauna abundance. *Crop Protection*, 28, 1045-1051.
(9) Belay D. & Foster J.E. (2010) Efficacies of habitat management techniques in managing maize stem borers in Ethiopia. *Crop Protection*, 29, 422-428.
(10) Khan Z.R., Midega C.A.O., Bruce T.J.A., Hooper A.M. & Pickett J.A. (2010) Exploiting phytochemicals for developing a 'push-pull' crop protection strategy for cereal farmers in Africa. *Journal of Experimental Botany*, 61, 4185-4196.

Additional reference

De Groote H., Vanlauwe B., Rutto E., Odhiambo G.D., Kanampiu F. & Khan Z.R. (2010) Economic analysis of different options in integrated pest and soil fertility management in maize systems of Western Kenya. *Agricultural Economics*, 41, 471-482.

4.4. Incorporate plant remains into the soil that produce weed-controlling chemicals

- **Weeds:** Six studies[1,2,3,5,8,10] (including six randomized, replicated, controlled tests) from Asia, Europe and North America examined the effect of allelopathic plant residues on weeds by comparing amended soils with weeded controls. Three studies[2,8,10] found a reduction in weed growth, and three[1,3,5] found effects varied between years, weed groups, or the type of weeding method in controls.
- Four[3,6,7,9] studies from Asia and North America examined the effect on weeds by comparing amended soils with unweeded controls. Two studies[3,7] found a reduction in weed growth, but one[7] found that residues applied too far in advance of crop planting had the reverse effect.
- Two studies[6,9] found that effects varied between trials, weed species or the type of residue used.
- **Weed control:** Two studies[4,9], including one randomized, replicated, controlled laboratory study, found that the decrease in weeds did not last beyond a few days or weeks after residue incorporation.
- **Pests:** One randomized, replicated, controlled study[5] in the Philippines found mixed effects on pests.
- **Crop growth:** Two[2,8] of three studies found that crop growth was inhibited by allelopathic residues, but these effects could be minimized by changing the timing of application. One study[1] found effects varied between years.
- **Yield:** Three randomized, replicated, controlled studies compared crop yields in amended plots with weeded controls and found positive[5], negative[7] and mixed effects[10]. Three studies compared amended plots with unweeded controls, two[3,7] found positive effects on yield and one[10] found mixed effects (depending on crop type).
- **Profit:** One study[3] found that amending soils increased profit compared to unweeded controls, but not compared to weeded controls.
- **Crops studied** were beans[4], cotton[10], maize[1,2,7,10], rice[5,8] and wheat[3].

Background

Weeds can be suppressed by amending the soil with plant residues that produce allelopathic chemicals (biological chemicals that affect the growth of other organisms) as they decay. Plant residues are typically incorporated into soils by ploughing or rotavation. In some cases allelopathic plants may be grown as cover crops prior to being incorporated into the soil (green manuring). We consider this to be part of the ecosystem service where these plants can be grown in the ecosystem in question (for example on farms in that region). Applying plant residues to the soil surface is part of the action 'Add mulch to crops' and incorporating plant residues for inducing soil suppression of pests and pathogens is considered part of 'Amend the soil with fresh plant material or crop residues' (actions for inclusion in future synopses).

A series of replicated, randomized, controlled trials in 1989-1990 in Maine, USA (*1*) found incorporating crimson clover *Trifolium incarnatum* residue reduced weed biomass and increased maize *Zea mays* growth in some years but

not all. In two of four experiments, the weed lambsquarters *Chenopodium album* had 36-65% lower biomass in crimson clover plots than in plots receiving oat residue and mineral fertilizer, whilst the other two experiments found no difference between treatments. Number of emerging lambsquarters and other weeds was higher in crimson clover plots in one year out of two. Maize biomass was higher in clover than fertilizer plots in one out of two years, by 13-47% in weed-free plots and 50-131% in weedy plots. All plots received crimson clover or oat residue, planted in summer of the previous year and killed and incorporated into the soil in May. Clover and control plots were unfertilized, while fertilizer plots received ammonium nitrate fertilizer at 45 kg N/ha. Maize and lambsquarters were sown in May or June, together in one experiment and lambsquarters alone in the other.

Two randomized, replicated, controlled trials in 1989-1990 in Maine, USA (*2*) (partly the same study as (*1*)) found that incorporating crimson clover *Trifolium incarnatum* residues into soil reduced emergence of lambsquarters *Chenopodium album* and other weeds compared to plots treated with nitrogen fertilizer. Maize *Zea mays* growth was initially 31% lower in plots with clover residue but returned to fertilized plot levels over the growing season. Lambsquarters growth was significantly reduced in plots of crimson clover compared to fertilized plots, with reductions of 64-81% two weeks after emergence and 37-42% lower at the final sampling date. Less maize dry matter was lost to weeds in the crimson clover treatment than the fertilized treatment (1989: 14 vs 36%; 1990: 0-2 vs 19-21%). Maize was grown in 3 x 9.1 m plots, each split to contain maize only or maize with lambsquarters. Other weeds were removed. There were six treatments: crimson clover residue, no fertilizer or residue and four levels of ammonium nitrate fertilizer (45, 90, 135, 180 kg N/ha). Crimson clover was sown at 84 kg/ha in May, then mown and incorporated 10-15 cm-deep on flowering. Maize was sown within 2 days of clover incorporation. A second trial in 1989 tested the effect of crimson clover residue applied to plots of lambsquarters.

A randomized, replicated, controlled trial in 1996-1997 in wheat *Triticum* sp. fields in Punjab province, Pakistan (*3*) found plots with sorghum *Sorghum bicolor* stalks incorporated into the soil had significantly fewer weeds (38-51 plants/m^2, 20-41% weed suppression) than unweeded controls (64 plants), similar numbers to hand-weeded controls (33 plants, 49% suppression) and more weeds than herbicide-treated controls (12 plants, 82% suppression). Wheat grain yield was 6-17% higher in sorghum residue plots than unweeded controls, 10% higher in hand-weeded than unweeded controls, and 22% higher in herbicide-treated than unweeded controls. The net benefits of sorghum residue (15,040-15,770 Rupees) were similar to those of unweeded controls (15,768 Rupees) but lower than hand-weeding (16,480 Rupees) or herbicide application (17,477 Rupees). After harvesting, sorghum was dried, cut into 2 cm pieces and incorporated 3-5 cm deep during seedbed preparation. Wheat was sown on 21 November 1996, at 45 kg/ha. Plots were 1.5 x 7.5 m with four replicates. There were six treatments: unweeded control; 2, 4, 6 t/ha sorghum residue; herbicide treatment: Chlorotololuron + MCPA at 2.5 kg/ha; hand weeding. Weed density and biomass were recorded in two 1 m^2 quadrats/plot, 60 or 90 days after sowing.

A randomized, replicated, controlled laboratory experiment in 1996 in Maine, USA (*4*) found that root growth of seedlings of the weed wild mustard *Sinapis arvensis* was reduced by 20% by extracts of soil containing red clover *Trifolium pratense* and wheat *Triticum aestivum* residues incorporated eight days previously, but not at any other time after incorporation. There were two treatments, each replicated four times: incorporated wheat crop stubble residue (approximately 30 kg/ha above ground dry matter biomass); incorporated wheat stubble and red clover *Trifolium pratense* residue (2,530 kg/ha). Residues were incorporated on 28 May 1996. Beans *Phaseolus vulgaris* and wild mustard were planted 17 days later. Approximately 25 soil samples/plot were taken 12 days before and 8, 21, 30, 41, 63 and 100 days after residue incorporation. Soil water extracts (5 ml) from the soil samples were applied to 20 pre-germinated wild mustard seedlings in the laboratory which were incubated at 20°C. Rootlet length was measured after 72 hours.

A randomized, replicated, controlled trial in 1987-1988 at two sites in Mindinao, Philippines (*5*) found that weight of broadleaved weeds was higher in plots of rice *Oryza sativa* amended with gliricidia *Gliricidia sepium* (averaging 3.8-51.3 g/m^2) than non-amended control plots (1.9-20.5 g/m^2) in 1988. No difference was found in 1987. Weight of grass weeds was similar between treatments in 1987 and varied between study sites in 1988. Amended plots had more rice seedling maggot *Atherigona oryzae* eggs (2.7-15.5 eggs/m crop row) than control plots (0.8-8.8 eggs) at one site in 1987-1988, but numbers were similar between treatments at the second site (0.4-25.8 eggs). White grub (Scarabaeidae) numbers were similar between amended and control treatments except at one site in 1988, when they were more abundant in the amended plots (1.7 vs 1.0 larvae/5 m crop row). Stem borer (Lepidoptera) damage was greater in amended plots (2.4-12.3 vs 1.4-5.5 deadhearts/m of row) in one of two sites in each year, but otherwise similar. Rice grain yields were higher in amended (0.79-1.51 t/ha) than control (0.09-0.83 t/ha) plots. Rice was planted between hedgerows at two 0.6 ha sites and amended with gliricidia (cut from hedgerows) or left without amendment. Treatments were replicated six times.

A series of four randomized, replicated trials in 1999-2001 in cut flower production systems in California, USA (*6*) found incorporating broccoli *Brassica oleracea* and other brassica plant residues had variable success in controlling weeds. One experiment found no effect on weed survival (redroot pigweed *Amaranthus retroflexus*, annual bluegrass *Poa annua*, little mallow *Malva parviflora*) as broccoli material (covered by tarpaulin) increased from 4.0 to 8.4 t dry matter/ha. One experiment found broccoli residue reduced bindweed *Convolvulus arvensis* populations compared to controls (approximately 56% reduction), while Brussels sprouts *B. oleracea* and horseradish *Armoracia lapathifolia* residues did not. One experiment found that broccoli residues and a tarpaulin reduced the number of common purslane plants compared to other tarpaulin treatments. Addition of a tarpaulin to plots with incorporated broccoli residue generally had no effect. Broccoli plant material was collected after floret harvesting and applied at 2.6-8.4 t/ha, approximately 10-30 cm deep. Plots were left uncovered, or covered with a tarpaulin sheet. There were four replicates. Weed species were counted in 0.25 m^2 quadrats.

A randomized, replicated, controlled trial in 2008-2009 in Iran (*7*) found incorporating rye *Secale cereale* plant material into the soil resulted in a

significant increase in weed density when material was incorporated 54 days before sowing maize *Zea mays*, but a significant reduction in weed density when incorporated 12 or 34 days before maize. Plots with material incorporated 54 days before maize showed a 1.1% decrease in maize grain production compared to unweeded controls, while incorporating material nearer the time of maize sowing increased maize grain production (4.2-7.9% increase). However, grain production in weeded controls was 39.6% higher than unweeded controls. Rye was sown as a cover crop in November 2008 at three different seeding rates and cut down 21-28 days before the plant material was incorporated. Controls for testing weed density were not sown with rye. Maize was sown on 12th June with controls divided into weed free and unweeded plots. Treatments were tested in 3 x 4 m plots replicated four times. Weed biomass and density was surveyed in 50 x 50 cm quadrats 4, 6 and 8 weeks after planting. The study does not separate the effects of growing a cover crop and incorporating plant material into the soil.

A greenhouse experiment and a replicated, controlled field trial in 2000-2001 in Cambodia (*8*) found incorporating rice *Oryza sativa* crop residue into the soil suppressed weed germination and growth, but also suppressed growth of the following rice crop. Greenhouse pots with amended soil had lower weed germination and establishment than non-amended pots (17-47% vs 71-75%). In field plots in 2000, rice crop residues reduced the dry weight of barnyardgrass *Echinochloa crus-galli* by 70-93%, depending on rice variety used. However, the rice crop dry weight was also suppressed by 66-85%. In 2001, a smaller amount of rice crop residue incorporated earlier in the season suppressed barnyardgrass by 21-32%, small umbrella sedge *Cyperus difformis* 15-23% and water primrose *Ludwigia octovalvis* 20-32%. Rice dry weight suppression was 1-6%. The field experiment ran in January-March 2000 and 2001. Residues of eight rice varieties were incorporated 0-10 cm deep. In 2000, barnyardgrass or rice was sown one week after 6 kg/plot crop residue was incorporated. In 2001, three weed species and one rice crop were sown two weeks after 4 kg/plot of crop residue. The greenhouse experiment used 16 plant lines and one non-residue control.

A set of three randomized, replicated, controlled field trials in central California, USA (*9*) found that incorporating residue of a sorghum-sudangrass hybrid (*Sorghum bicolor* x *S. sudanense* 'sudex') into the soil reduced weed growth, but that this effect was temporary. In the first experiment, growing and incorporating sudex reduced weed growth by 35% (136 g dry weight weed biomass vs 208 g in control plots). In the other two experiments, weed growth was reduced by 61-89% compared to control plots 50 days after treatment, but after 57 days in the second experiment and 106 days in the third experiment this difference had disappeared. Sudex was planted in six rows in raised beds and shredded at 1.4-2.0 m tall. Experiment 1 had three treatments with four replicates in 1 m-long plots: sudex grown, shredded and left as a mulch; grown, shredded and incorporated; no sudex grown or residue added. Experiments 2 and 3 had four replicates in 4.5 x 1.5 m plots. Treatments included those from experiment 1, plus two additional treatments: shreddings added to fallow plot where no sudex had been grown; shreddings removed but roots and 3-5 cm stubble left in plots. Weed biomass was calculated by removing material from a 0.093-1 m^2 area.

A randomized, replicated, controlled trial in 2005-2007 in northern Greece (*10*) found that incorporating oregano *Origanum vulgare* into the soil reduced

the abundance of three weed species in cotton *Gossypium hirsutum* and maize *Zea mays*. In cotton, green manure reduced numbers of the weed common purslane *Portulaca oleracea* by 30-55% (55-85 vs 121 plants/m^2), barnyard grass *Echinochloa crus-galli* by 48-52% (23-25 vs 48) and bristly foxtail *Setaria verticillata* by 43-86% (1-4 vs 7). Maize plots with green manure had 0-45% fewer common purslane (71-128 vs 129), 38-46% fewer barnyard grass (7-8 vs 13) and 60-80% fewer bristly foxtail (1-2 vs 5). The cotton yield was significantly lower in green manure treatments than in a weed free control, but not different to (and in once case higher than) an unweeded control. Maize silage and grain yields were similar between treatments. There were four oregano green manure treatments (plants from four locations, selected for high concentrations of potential allelopathic chemicals) and two controls without green manure (one weeded) replicated four times in 9 x 5 m plots. Oregano was incorporated 8-10 cm deep before flowering. Cotton and corn were planted five days later.

(1) Dyck E. & Liebman M. (1995) Crop-weed interference as influenced by a leguminous or synthetic fertilizer nitrogen source: II. rotation experiments with crimson clover, field corn, and lambsquarters. *Agriculture, Ecosystems & Environment*, 56, 109-120.
(2) Dyck E., Liebman M. & Erich M.S. (1995) Crop-weed interference as influenced by a leguminous or synthetic fertilizer nitrogen source: I. doublecropping experiments with crimson clover, sweet corn, and lambsquarters. *Agriculture, Ecosystems & Environment*, 56, 93-108.
(3) Cheema Z.A. & Khaliq A. (2000) Use of sorghum allelopathic properties to control weeds in irrigated wheat in a semi arid region of Punjab. *Agriculture, Ecosystems & Environment*, 79, 105-112.
(4) Ohno T., Doolan K., Zibilske L.M., Liebman M., Gallandt E.R. & Berube C. (2000) Phytotoxic effects of red clover amended soils on wild mustard seedling growth. *Agriculture, Ecosystems & Environment*, 78, 187-192.
(5) MacLean R.H., Litsinger J.A., Moody K., Watson A.K. & Libetario E.M. (2003) Impact of *Gliricidia sepium* and *Cassia spectabilis* hedgerows on weeds and insect pests of upland rice. *Agriculture, Ecosystems & Environment*, 94, 275-288.
(6) Zasada I.A., Ferris H., Elmore C.L., Roncoroni J.A., MacDonald J.A., Bolkan L.R.*, et al.* (2003) Field application of brassicaceous amendments for control of soilborne pests and pathogens. *Plant Health Progress*, doi:10.1094/PHP-2003-1120-01-RS.
(7) Mafakheri S., Ardakani M.R., Meighani F., Mirhadi M.J. & Vazan S. (2010) Rye cover crop management affects weeds and yield of corn (*Zea mays* L.). *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 38, 117-123.
(8) Pheng S., Olofsdotter M., Jahn G. & Adkins S. (2010) Use of phytotoxic rice crop residues for weed management. *Weed Biology and Management*, 10, 176-184.
(9) Stapleton J.J., Summers C.G., Mitchell J.P. & Prather T.S. (2010) Deleterious activity of cultivated grasses (Poaceae) and residues on soilborne fungal, nematode and weed pests. *Phytoparasitica*, 38, 61-69.
(10) Vasilakoglou I., Dhima K., Anastassopoulos E., Lithourgidis A., Gougoulias N. & Chouliaras N. (2011) Oregano green manure for weed suppression in sustainable cotton and corn fields. *Weed Biology and Management*, 11, 38-48.

5. Perennial farming

5.1. Allow natural regeneration of ground cover beneath perennial crops

- **Natural enemies on crop trees and vines:** Five studies[2,4,6,8,9] (including one replicated, randomized, controlled test) from Australia, China, Italy and Portugal compared natural and bare ground covers by measuring numbers of natural enemies in fruit tree or vine canopies. Three[4,6,8] found effects varied between groups of natural enemies, two[2,9] found no difference. Two studies[2,7] from Australia and France compared natural to sown ground cover and found no effect on enemies in crop canopies.
- **Natural enemies on the ground:** Five studies[1,3,5,6,9] (including three replicated, randomized, controlled trials) from Australia, Canada, China, France, and Spain compared natural and bare ground covers by measuring natural enemies on the ground. Two studies[1,6] found more natural enemies in natural ground cover, but in one[6] the effects were only short-term for most natural enemy groups. Three studies[3,5,9] found mixed effects, with higher numbers of some natural enemy groups but not others. Two studies[1,2] compared natural and sown ground covers, one study[1] found more natural enemies and one[2] found no effect.
- **Pests and crop damage**: Four studies[4,6,7,9] (three controlled, one also replicated and randomized) from Italy, Australia and China measured pests and crop damage in regenerated and bare ground covers. Two studies[6,9] found fewer pests, whilst two studies[4,7] found effects on pests and crop damage varied for different pest or disease groups. One study[2] found more pests in natural than in sown ground covers.
- **Crops studied** were apple[1,3,7], grape[4,6], lemon[8], olive[5] and pear[2,9].

Background

This includes studies allowing the natural regeneration of weeds beneath perennial crops to enhance natural enemy populations. This includes studies testing the impact of tillage versus no tillage (or other types of soil disturbance) or herbicide versus no herbicide under perennial crops, where these practices are used to control weeds. Studies using naturally regenerated ground cover as a control treatment to compare with other actions (e.g. 'Grow plants that provide nectar or pollen resources' and 'Grow plants that provide supplementary prey for natural enemies') are not included here. Ground-dwelling invertebrates are frequently surveyed using pitfall traps – small pots buried in the ground up to their rim and left empty or filled with liquid preservatives or water.

Here we present evidence from nine of 13 studies testing this action.

A randomized, replicated, controlled, before-and-after trial in 1975-1977 in apple *Malus domestica* orchards in Ontario, Canada (*1*) found more ground beetles (Carabidae) in naturally regenerated ground cover (29-98 ground beetles/m^2) than in bare ground cover (4-7 ground beetles) in August 1976 to August 1977, in shallow 5 cm-deep soil samples. Soil cores to 30 cm-depth found a similar effect, with 42-305 ground beetles/m^2 in natural ground cover compared with 0-66 ground beetles in bare ground. More ground beetles also

occurred in natural ground cover than in creeping red fescue *Festuca rubra* (7-54 and 28-122 ground beetles/m^2, in shallow and deep samples respectively) or perennial ryegrass *Lolium perenne* (0-34 and 28-122 ground beetles/m^2) sown ground covers. Pitfall trapping found no effect of ground cover treatments. Naturally regenerated, bare (tilled), creeping red fescue and perennial ryegrass ground cover treatments were tested in 24 x 18 m plots (containing 18 apple trees), replicated five times each. Natural plots were untilled from 1975 to 1977. Other treatments were tilled weekly in May 1976 with fescue and ryegrass plots sown in early June 1976. Shallow and deep soil samples were taken at three and five locations/plot, respectively.

A controlled study in a pear *Pyrus communis* orchard in Drôme, France (*2*) found that the ratio of beneficial to plant-eating invertebrates was similar in pear tree canopies over naturally regenerated (0.05 natural enemies to each pest), bare (0.04 natural enemies) and sown (0.06 natural enemies) ground covers. Flies (Empididae), leaf bugs and plant bugs (Miridae) were the most numerous enemies in trees over regenerated ground covers. Similar numbers of natural enemies were found in regenerated and sown plants on the ground. However, regenerated plants had nearly two times more plant-eating invertebrates than sown plants so there were 0.06 natural enemies to each pest in the former vs 0.09 natural enemies to each pest in the latter. More natural enemies (for each pest) occurred in regenerated plants than in the tree canopies. Natural ground cover (established for 10 years), bare ground (created with glyphosate in March 1994) and sown ground cover treatments (planted in September 1993) each occupied one-third of the orchard (five rows between trees). Sown ground covers comprised ryegrass *Lolium perenne*, white mustard *Sinapis alba* and white clover *Trifolium repens*. Insects were sampled by beating branches in trees and using a sweepnet in ground covers.

A replicated, randomized and controlled study in an apple *Malus domestica* orchard in Asturies, Spain in 2000 (*3*) found that ground beetle (Carabidae) abundance was similar in plots with naturally regenerated ground cover (33 captures/trap) and rotovated control plots (48 captures). The second most common ground beetle species, *Pseudophonus rufipes* was significantly less numerous in the vegetated plots (0.13 captures/trap) than in the control (28 captures). Treatment blocks (comprising a row of 11 trees) were replicated four times in the 5 ha orchard. The regenerated ground cover was mowed three times in April-July and the control was rotovated in early spring and late August. Ground beetles were captured in pitfall traps of 6.5 cm diameter in August-November with two traps per plot.

A controlled study in 2002-2004 in a vineyard in Sardinia, Italy (*4*) found similar numbers of lacewings (Neuroptera) in a plot with regenerated ground cover (5-38 adults/plot) and a tilled plot (1-27 adults). Fewer spiders (Araneae) occurred in grape *Vitis vinifera* bunches in the ground cover plot (19-85 individuals/100 bunches) than in the tilled plot (29-108 individuals), but the ground cover plot had more spiders on vine trunks (371-440 versus 117-338 individuals/plot). Vine mealybug *Planococcus ficus* abundance did not differ consistently between plots, but infestations were higher in the ground cover (28-32% of bunches infested) than the tilled plot (17-18%) in 2003-2004, and crop damage was also higher in the ground cover plot in 2004 (28% versus 12% of bunches damaged). Infestations by second and third generation European

grapevine moth *Lobesia botrana* were smaller in the ground cover plot (12-21% of bunches infested) compared to the tilled plot (20-40%) in 2002-2004. Grey mould *Botrytis cinerea* and sour rot *Geotrichum candidum* damage was also less in the ground cover (2-13% of bunches damaged) than the tilled plot (12-42%) in 2002-2003 but not in 2004. Ground cover was naturally regenerated and mowed in one 0.5 ha plot, and ploughed and grubbed to control weeds in another 0.5 ha plot.

A site comparison in 2005 and 2006 on two olive *Olea europaea* orchard plots coppiced in 1956 in the Bouches-du-Rhône, France (*5*) found the plot with undisturbed ground cover had more spiders (Araneae) and ground beetles (Carabidae) (885 spiders, 69-206 ground beetles) than the plot where ground cover was ploughed (515 spiders, 27-53 ground beetles). There was a higher proportion of known predatory rove beetles (Staphylinidae) and ground beetles in the plot with undisturbed ground cover (19 and 30%) than in the ploughed plot (9 and 17%). Ground beetle specie richness was higher in the orchard with undisturbed ground cover but the number of spider families was similar (undisturbed ground cover: 16 ground beetle species, 18 spider families; ploughed cover: 11 ground beetle species, 17 spider families). In 2005, rove beetle abundance was similar between orchards but species richness was higher in the disturbed ground cover orchard (undisturbed ground cover: 23 species; ploughed cover: 29 species). In spring 2006, rove beetle abundance was higher in the disturbed ground cover plot. One plot had permanent vegetation cover between rows and chemical weeding within the rows. Vegetation between rows in the second orchard was disturbed using a disc plough.

A replicated, randomized and controlled study in a grape *Vitis vinifera* vineyard in Victoria, Australia in 2003-2004 (*6*) found that predatory ants (Formicidae) were more abundant in untilled plots containing resident vegetation (averaging 57 captures/plot) than tilled plots (35 captures) in the four months following tillage. Numbers of other ground-living natural enemies, including earwigs (Dermaptera), centipedes (Lithobiida), millipedes (Julida) and spiders (Araneae), were also greater in untilled than tilled plots in the first or second month after tillage, but similar thereafter. Pest antlike flower beetles (Anthicidae) were less abundant in untilled (averaging 0.6 captures/plot) than tilled (2.2 captures) plots across all months. In the canopy, parasitoid wasps (Trichogrammatidae) were more abundant in untilled (averaging 5 captures) than tilled plots (2 captures) in one month, but were similar a month later. In each of five 288 m^2 plots, half the area was tilled (15 cm depth) and half was left with natural resident vegetation (grasses and weeds).

A replicated, randomized, controlled study in south-eastern Australia (*7*) found that numbers of parasitoid (Hymenoptera), lacewing (Chrysopidae and Hemerobiidae) and ladybird (Coccinellidae) natural enemies were similar in apple tree *Malus domestica* canopies over naturally regenerated and commercial grass ground covers. Damage caused by the majority of pests and diseases was similar between treatments (including apple dimpling bug and russett) but damage by *Helicoverpa* was significantly less for apples with naturally regenerated ground cover (causing 1% of the damage to apples) than with grass mix (5%) at one site. Apple diameter and weight were similar (73-75 mm diameter, 165-188 g) for apple trees in both treatments. Treatments were applied at three sites (two included the regeneration treatment but all three

received the grass mix) and in plots of 265-288 m^2 replicated four times. Naturally regenerating species included a mix of flowering plants and grasses.

A replicated, randomized and controlled study in three lemon *Citrus limon* orchards in Oeste, Portugal in 2002-2003 (*8*) found that spiders (Araneae), ladybirds (Coccinellidae) and parasitoid wasps (Hymenoptera) were more abundant in lemon trees above naturally regenerated vegetation than above bare ground controls, when sampled by both beating and suction. Lacewings (Chrysopidae) were more abundant in lemon trees over naturally regenerated ground covers (3.0 individuals/25 trees) than controls (0.5 individuals) in suction samples, but beating samples found no difference. Ground cover treatments provided the highest numbers of lacewings, ladybirds and parasitoid wasps (relative to controls) in spring and summer, but not in winter. The three orchards were split into plots of 0.6 ha which were allowed to naturally regenerate or kept bare using herbicide. Regenerated plots were mown twice per year and comprised a mixture of grasses and flowering plants, dominated by annual meadow grass *Poa annua*.

A site comparison study in two pear *Pyrus* spp. orchards in Daxing District, China (*9*) found that total numbers of natural enemies were similar between plots of naturally regenerated ground cover (averaging 337 individuals/year) and bare, tilled plots (306 individuals/year) during March to September, 2006-2008. Pest numbers were lower in regenerated (averaging 2113 individuals/year) than bare, tilled plots (3214 individuals/year). The seven-spot ladybird *Coccinella septempunctata*, predatory mite *Phytoseiulus persimilis* and green lacewing *Chrysoperla sinica* were the dominant natural enemies on ground cover plants and were more abundant in regenerated than tilled plots from around early June to mid-July. Three plots of 50 x 67 m in one orchard were allowed to grow natural grasses (Poaceae) and were compared with three plots of tilled bare ground in a separate orchard. Invertebrates were counted using visual surveys, canopy traps and sweeps of ground cover vegetation.

(1) Holliday N.J. & Hagley E.A.C. (1984) The effect of sod type on the occurrence of ground beetles (Coleoptera: Carabidae) in a pest management apple orchard. *Canadian Entomologist*, 116, 165-171.

(2) Rieux R., Simon S. & Defrance H. (1999) Role of hedgerows and ground cover management on arthropod populations in pear orchards. *Agriculture, Ecosystems & Environment*, 73, 119-127.

(3) Minarro M. & Dapena E. (2003) Effects of groundcover management on ground beetles (Coleoptera: Carabidae) in an apple orchard. *Applied Soil Ecology*, 23, 111-117.

(4) Serra G., Lentini A., Verdinelli M. & Delrio G. (2006) Effects of cover crop management on grape pests in a Mediterranean environment. *Bulletin OILB/SROP*, 29, 209-214.

(5) Ricard J.M., Garcin A., Damian-Picollet S. & Bousquet L. (2007) Biodiversité des arthropodes du sol en verger d'olivier: a la recherche de predateurs de la mouche de l'olive. *Infos-Ctifl*, 25-30.

(6) Sharley D.J., Hoffmann A.A. & Thomson L.J. (2008) The effects of soil tillage on beneficial invertebrates within the vineyard. *Agricultural and Forest Entomology*, 10, 233-243.

(7) Bone N.J., Thomson L.J., Ridland P.M., Cole P. & Hoffmann A.A. (2009) Cover crops in Victorian apple orchards: effects on production, natural enemies and pests across a season. *Crop Protection*, 28, 675-683.

(8) Silva E.B., Franco J.C., Vasconcelos T. & Branco M. (2010) Effect of ground cover vegetation on the abundance and diversity of beneficial arthropods in citrus orchards. *Bulletin of Entomological Research*, 100, 489-499.

(9) Beizhou S., Zhang J., Jinghui H., Hongying W., Yun K. & Yuncong Y. (2011) Temporal dynamics of the arthropod community in pear orchards intercropped with aromatic plants. *Pest Management Science*, 67, 1107-1114.

5.2. Exclude ants that protect pests

- **Parasitism:** One[4] of two replicated, controlled studies (one also randomized) from Japan and the USA found greater parasitism of pests by natural enemies when ants were excluded from trees. The other study[6] found greater parasitism at one site but no effect at another.
- **Natural enemies:** Five studies[1,3,5,6,7] (including four randomized, replicated, controlled trials) from Japan, Switzerland and the USA found effects varied between natural enemy species and groups, sampling dates, sites, crop varieties and ground cover types beneath trees.
- **Pests:** Three[4,6,7] of seven studies (including four randomized, replicated, controlled trials) found fewer pests and another[1] found fewer pests at times of peak abundance only. One study[5] found mixed effects depending on date and other actions taken simultaneously (predator attractant and ground cover treatments). One study[2] found no effect.
- **Damage and tree growth:** One study[3] found no effect on damage to tree foliage but one study[7] found greater tree growth.
- **Ants:** Six studies[1,2,3,5,6,7] found that glue or pesticide barriers reduced ant numbers in tree or vine canopies. One study[1] found that citrus oil barriers had no effect.
- **Crops studied** were cherimoyas[2], cherry[3,7], grape[6], grapefruit[1], orange[1], pecan[5] and satsuma mandarin[4].

Background

This involves applying adhesive substances or chemicals to the trunks of perennial crop trees, preventing pest-protecting ants from reaching the branches. Many ants form mutualistic relationships with insect pests (e.g. feeding on honeydew secreted by bugs (Hemiptera) such as aphids), defending them from predators and parasitoids. Excluding these ants may therefore increase predation and parasitism rates by beneficial invertebrates. See also 'Isolate colonies of beneficial ants' for managing ants that act as natural predators and improve pest control.

A randomized, replicated, controlled study in 1984-1985 in California, USA (*1*) found fewer spider mite destroyers *Stethorus picipes* in navel orange *Citrus sinensis* trees with insecticide barriers to exclude ants (0.2-0.8 destroyers/sticky card) vs control trees (15-32 destroyers) in autumn, but no difference in summer and winter. The same effect was found in grapefruit *Citrus paradisi*, but not in Valencia oranges. Predatory mite *Euseius tularensis* numbers were similar between treatments. Fewer citrus red mites *Panonychus citri* occurred in trees with vs without ant barriers (2-65 vs 17-173 mites/tree, respectively) in orange orchards during peak numbers in late summer and the same effect was found in a grapefruit orchard during an autumn peak (approximately 75 vs 200 mites/tree). Argentine ants *Linepithema humile* were successfully excluded from orange trees with insecticide barriers (0 ants/minute/tree with barriers applied vs 14-158 in control trees) but a limonene citrus oil barrier had no effect (19-219 ants/minute/tree). Plots of orange trees (in two orchards) were assigned to insecticide (90 ml of 1% chlorpyrifos applied at the base of trees), citrus oil (135

ml of 15% limonene) or no-barrier treatments. Plots of grapefruit (in one orchard) were assigned to insecticide or no-barrier treatments only.

A randomized, replicated, controlled study in 1984 in California, USA (*2*) tested three ant exclusion techniques and found lower Argentine ant *Linepithema humile* infestation when sticky band barriers (ant activity rating of 0.52) and chlorpyrifos insecticide (rating of 1.0) were applied than when baited traps (rating of 1.39) or no ant exclusion (rating of 1.43) were applied to cherimoyas *Annona cherimola* trees. Mealybug (namely *Pseudococcus longispinus*) infestation was closely related to Argentine ant activity but was similar (when tested statistically) between the ant exclusion treatments (infestation ratings of 0.1, 0.3, 0.5 and 0.7 for sticky band, chlorphyrifos, baited trap and no exclusion treatments, respectively). Sticky band barriers comprised of Tangle-trap aerosol sprayed in a band (of 3 inch-width) around tree trunks. In the insecticide treatment, chlorpyrifos was applied to the base of the trunk and surrounding 12 inches of soil. The baited trap contained a sugar/carboxymethylcellulose bait and Amdro pesticide. Treatments were replicated four times with three cherimoyas trees/replicate. Ant activity was rated 0 (< 1 ant/minute passing a point on the trunk) through to 5 (51-100 ants/minute). Mealybug infestation was rated 0 (no mealybugs) to 3 (over half of fruit surface area infested).

A randomized, replicated, controlled study in 1993 in Extremadura, Spain (*3*) found more natural predators on cherry *Prunus* sp. trees with ant-excluding glue (averaging 466-827 predators/100,000 aphids) than on trees treated with insecticide (42-238 predators) in June-July, and more than on untreated trees (94 predators/100,000 aphids) in June. Numbers were similar between treatments on other dates. Predators included ladybirds (Coccinellidae), flies (Chamaemyiidae and Syrphidae) and lacewings (*Chrysopa* sp.). Fewer aphids (Aphidoidea) occurred on trees with glue barriers (2,799-78,517 aphids/tree) and insecticide treatments (27-28,487 aphids) than on untreated trees (61,470-269,310 aphids) in May-July. Damage to foliage in October was similar in trees with glue barriers (249 shoots affected/tree), a March insecticide treatment (138 shoots) and no treatment (415 shoots), but an April insecticide treatment resulted in less damage (87 shoots). Glue barriers reduced ant (Formicidae) numbers vs untreated and insecticide-treated trees (0-1 vs 4-24 ants) in May-June but numbers later became similar when ants gained access to canopies via weeds and farm tools. Four treatments were replicated four times (one tree/treatment/replicate): glue applied around tree trunks, pirimicarb application (100 g/Hl) to tree canopies in March, pirimicarb application in April, and an untreated control.

A replicated, controlled study in 1989-1991 in Wakayama Prefecture, Japan (*4*) found more parasitism of red wax scale *Ceroplastes rubens* by first generation wasps *Anicetus beneficus* on twigs where black garden ants *Lasius niger* were excluded with glue barriers (14% scale insects parasitized) than on twigs without glue barriers (5% parasitized). Second generation wasps parasitized marginally more scales (13.5%) on twigs with than without barriers (8%). Red wax scale survival rate was lower on twigs with (2.1%) than without (4.6%) ant barriers. Twigs with barriers had 1,582-3,122 young scales and 13-64 egg-laying adult scales, compared with 2,791-4,028 young and 166-187 egg-laying adults on twigs without barriers. Scale population increase was 10 times less on twigs with

than without barriers over two years. A pair of one-year old twigs was selected on each of 12 satsuma mandarin *Citrus unshiu* trees in a 1 ha orchard area in June 1989. One twig in each pair received glue at the base of the stem to exclude ants. Scales were counted in August-October 1989 and in May-June 1990 to assess parasitism, which was determined by body colour. The experiment was repeated on nearby twigs (in the same trees) in 1990-1991.

A randomized, replicated, controlled study in 1993-1994 in four pecan *Carya illinoinensis* orchards in Alabama and Georgia, USA (*5*) found that beneficial insects were not affected by insecticide barriers to exclude ants in 1993. Ladybeetle (Coccinellidae) numbers were similar or showed inconsistent differences between trees with and without ant barriers in 1994, but at one site more were found in trees with (0.35-0.50 ladybeetles/bud) than without ant barriers (0.17-0.32 ladybeetles) in mid-May, when cover crops were also planted under trees. Barriers had no or inconsistent effects on aphids, for example fewer blackmargined aphids *Monellia caryella* occurred in trees with than without ant barriers on three sampling dates at one site, but the opposite was found on two other dates. Evidence from one of two sites showed that numbers of blackmargined aphids during the spring peak in 1994 were lowest when combining ant barrier treatments with cover crops and a foliage spray to attract natural enemies. Barriers successfully prevented red imported fire ant *Solenopsis invicta* from accessing pecan trees. Ant barriers were chlorpyrifos sprays (1 kg/ha) applied in spring in a 1 m-width band around tree trunks. Barriers were re-applied if ants were observed overcoming the barrier.

A randomized, replicated, controlled study in 1998-1999 in California, USA (*6*) found greater parasitism of mealybugs *Pseudococcus* spp. by parasitoid wasps (Encyrtidae) in grapevines *Vitis vinifera* with vs grapevines without ant barriers (21-68% vs 10-11% parasitized, respectively) in the Central Coast region. There was no effect in the North Coast region (0.00-0.02% vs 0.004-0.005%). Fewer mealybug destroyers *Cryptolaemus montrouzieri* (introduced before the study) occurred in vines with vs without ant barriers (0.07-0.09 vs 0.29-0.31 mealybug destroyers/vine) in the Central Coast. The same effect occurred in the North Coast in 1999 but not 1998. Lacewing (Chrysopidae) numbers were unaffected in both regions (0.08-0.24 vs 0.05-0.20 lacewings/vine). Fewer obscure mealybugs *Pseudococcus viburni* occurred in vines with vs without ant barriers in the Central Coast (12-59 vs 129-303 mealybugs/vine, respectively) and grape mealybugs *Pseudococcus maritimus* were similarly affected in the North Coast (6-28 vs 54-69 mealybugs). Fewer Argentine ants *Linepithema humile* occurred in vines with barriers (0.0-0.9 ants/2 minutes/vine) vs vines without barriers (25-39 ants). Barriers were made by stripping bark from vine trunks and covering the exposed wood with duct tape coated in Tanglefoot Pest Barrier (re-applied when necessary). Three vineyards across two regions were studied, with six replicates/site.

A replicated, controlled study in 2008-2009 near Bern, Switzerland (*7*) found fewer earwigs *Forficula auricularia* (enemies of black cherry aphid *Myzus cerasi*) on trees with glue barriers to exclude ants (0.2 earwigs/tree) than trees without barriers (2.1 earwigs). More hoverfly (Syrphidae) eggs and larvae were found on trees with than without barriers in mid-May (1.9-3.3 vs 0.6-2.1 eggs or larvae/twig, respectively) but the opposite occurred in late May-early June (0.0-1.0 vs 0.6-1.9 eggs or larvae/twig). Barriers reduced the total number of

ladybirds (Coccinellidae) counted across the season (late April to early June 2009) but differences between treatments were not consistent across individual sampling dates. Fewer ants (Formicidae) occurred on trees with barriers at all sampling dates (0.0-0.2 ants/twig with barriers vs 0.7-8.2 ants without barriers) and aphids were also fewer from mid-May to early June (0-25 vs 90-360 aphids/twig). Wild cherry trees *Prunus avium* with barriers grew more new wood than trees without barriers. Four-year-old cherry trees were planted at 30 sites in spring 2008 and black cherry aphids were released onto four trees/site in mid-April 2009. A 7 cm-width glue ring was attached around the main stem of two trees and renewed monthly to exclude ants.

(1) Haney P.B., Luck R.F. & Moreno D.S. (1987) Increases in densities of the citrus red mite, *Panonychus citri* (Acarina: Tetranychidae), in association with the Argentine ant, *Iridomyrmex humilis* (Hymenoptera: Formicidae), in southern California citrus. *Entomophaga*, 32, 49-57.
(2) Phillips P.A., Bekey R.S. & Goodall G.E. (1987) Argentine ant management in cherimoyas. *California Agriculture*, 41, 8-9.
(3) Perez J.A., Garcia T., Arias A. & Martinez de Velasco D. (1995) La cola entomologica, un metodo alternativo a la lucha con insecticidas contra el pulgon negro del cerezo (*Myzus cerasi* F.). *Boletin de Sanidad Vegetal, Plagas*, 21, 213-222.
(4) Itioka T. & Inoue T. (1996) The consequences of ant-attendance to the biological control of the red wax scale insect *Ceroplastes rubens* by *Anicetus beneficus*. *Journal of Applied Ecology*, 33, 609-618.
(5) Dutcher J.D., Estes P.M. & Dutcher M.J. (1999) Interactions in entomology: aphids, aphidophaga and ants in pecan orchards. *Journal of Entomological Science*, 34, 40-56.
(6) Daane K.M., Sime K.R., Fallon J. & Cooper M.L. (2007) Impacts of Argentine ants on mealybugs and their natural enemies in California's coastal vineyards. *Ecological Entomology*, 32, 583-596.
(7) Stutz S. & Entling M.H. (2011) Effects of the landscape context on aphid-ant-predator interactions on cherry trees. *Biological Control*, 57, 37-43.

5.3. Isolate colonies of beneficial ants

- **Natural enemies:** One replicated, controlled study[1] from Australia found predatory ants occupied more cashew trees when colonies were kept isolated.
- **Pest damage and yield:** The same study[1] found lower pest damage to cashews and higher yields.
- The **crop studied** was cashew[1].

Background

This action involves pruning perennial crop trees to isolate ant colonies living in the tree canopy. Where ants act as natural predators, this action may improve pest control by reducing the time, energy and ant population losses incurred when rival ant colonies interact and viciously fight each other. This differs from the action 'Exclude ants that protect pests' for managing ants that limit rather than benefit natural pest control (for inclusion in a future synopsis).

A replicated, controlled experiment in 1996-1997 in Northern Territory, Australia (*1*) found predatory green ants *Oecophylla smaragdina* occupied more cashew *Anacardium occidentale* trees when their colonies were kept isolated from each other (100% of trees occupied) than when left to interact normally (52-66%). Damage by tea mosquito bugs *Helopeltis pernicialis*, mango tip-borers *Penicillaria jocosatrix* and fruit spotting bugs *Amblypelta lutescens* was 1% in the

colony isolation treatment compared to 23%, 8% and 14% (for these pests respectively) in the non-isolation treatment. Yields were higher in the colony isolation treatment (10.5 and 14.5 kg/tree, in 1996 and 1997 respectively) than the non-isolation treatment (4.6 and 3.9 kg/tree). Ant colonies were isolated by pruning tree branches that linked a colony to other trees occupied by rival colonies. Four colonies in 14 trees were isolated from April onwards in 1996, and five colonies in 16 trees were isolated from March onwards in 1997 (at the same site). In nearby parts of the plantation, 9-12 colonies were identified but not manipulated, creating non-isolated controls. The percentage of flower shoots damaged by pests was recorded fortnightly from June to November, in the bottom and middle of the tree canopy.

(1) Peng R., Christian K. & Gibb K. (2001) Potential of using colonies of the green ant, *Oecophylla smaragdina* (F.), to control cashew insect pests. *Proceedings of the Sixth Workshop for Tropical Agricultural Entomologists, May 1998*. Darwin, Australia. Technical Bulletin, No. 288, pp 81-93.

6. Livestock farming and pasture

6.1. Delay mowing or first grazing date on pasture or grassland

- **Natural enemy abundance:** One replicated, randomized, controlled study[8] found fewer predatory spiders with delayed cutting. Three studies[5,6,9] from the UK (two of them replicated, randomized and controlled) found no change in insect predator numbers and one replicated study from Sweden[11] found mixed effects between different predator groups.
- **Natural enemy diversity:** One replicated study[11] from Sweden found a decrease in ant diversity with delayed cutting and one replicated, randomized, controlled study[10] from the UK found no effect on spider and beetle diversity.
- **Pests:** One[4] of two replicated, randomized, controlled studies from the UK and USA found more pest insects in late-cut plots and one[12] found no effect..
- **Insects in general:** Four replicated, randomized, controlled studies measured the abundance of insect groups without classifying them as pests or natural enemies. One UK study[1,2] found lower numbers in late-cut plots, while two[3,9] found effects varied between groups. Two studies[4,12] from the UK and USA found no effect on insect numbers.
- **Crops studied** were barley[8], bird's-foot trefoil[4], clovers[6,12], fescues[4], rapeseed[8], ryegrass[4,6,9,10,12], other grasses[1,2,3,4,9,12] and wheat[8].

Background

This action involves delaying mowing or the onset of grazing on grasslands until later in the year. This may reduce damage to insect and spider natural enemy populations (or increase damage to pests) at sensitive points in their lifecycles, such as before overwintered individuals begin breeding. Ground-living invertebrates can be sampled by suction sampling, using a vacuum to suck-up and collect specimens for a given time or area of ground.

A replicated, randomized, controlled trial in 1973-1975 on a tall oatgrass *Arrhenatherum elatius*-dominated grassland in Cambridgeshire, UK (*1*) (same study as (*2*) and (*3*)) found delaying the mowing date resulted in fewer bugs (Heteroptera). There were more bugs in plots cut in May only (averaging 176 individuals/plot) than plots cut in July only (52 individuals). Uncut plots had 288 individuals/plot. Four cutting treatments (uncut, May cut, July cut, May and July cuts) were replicated four times and randomly allocated to plots of 16 x 12 m. Invertebrates were sampled in October 1972-December 1975 using a D-Vac suction sampler.

A replicated, randomized, controlled trial in 1973-1975 on a tall oatgrass *Arrhenatherum elatius*-dominated grassland in Cambridgeshire, UK (*2*) (same study as (*1*) and (*3*)) found that delaying mowing resulted in significantly fewer leafhoppers (Auchenorrhyncha). There was an average of 4,546 individuals/plot in plots cut in May compared to 1,906 individuals in plots cut in July. Uncut plots had similar numbers of leafhoppers (5,666 individuals) to plots cut in May. There

was no difference in the number of species between cutting treatments. Four cutting treatments (uncut, May cut, July cut, May and July cuts) were replicated four times and randomly allocated to plots of 16 x 12 m. Invertebrates were sampled in October 1972-December 1975 using a D-Vac suction sampler.

A replicated, randomized, controlled trial in 1973-1975 on a tall oatgrass *Arrhenatherum elatius*-dominated grassland in Cambridgeshire, UK (*3*) (same study as (*1*) and (*2*)) found that three of seven leafhopper (Auchenorrhyncha) species were more abundant on plots cut in July than in plots cut in May, in at least one of the three years. There were significantly more *Macrosteles laevis* and *Neophilaenus campestris* individuals on plots cut in July-only than May-only in all three years (*M. laevis*: 0.8-1.9 individuals in May-only vs 0.1 individuals in July-only plots; *N. campestris*: 1.0-2.5 vs 0.0-0.3). There were more *Adarrus ocellaris* leafhoppers on plots cut in July-only than May-only in 1975 (10.3 vs 1.5 individuals). However, one leafhopper species, *Recilia coronifera*, was less abundant on plots cut in July than May-only in 1975 (0.0 vs 0.4 individuals). Four cutting treatments (uncut, May cut, July cut, May and July cuts) were replicated four times and randomly allocated to plots of 16 x 12 m. Invertebrates were sampled in October 1972-December 1975 using a D-Vac suction sampler.

A replicated, randomized, controlled trial on plots of bird's-foot trefoil *Lotus corniculatus* pasture mixes in 1984-1985 at two sites in West Virginia, USA (*4*) found aphids (Aphididae) were significantly more abundant in plots cut first in July than those cut in June (4.5 vs 3.7 aphids) at one site. Numbers of all other insects, including spittlebugs (Cercopidae), leafhoppers-planthoppers (Cicadellidae and Delphacidae) and mirids (Miridae), were not significantly different between plots cut in June and plots cut in July. Forage yields did not differ significantly between cutting treatments. Plots were cut on 15 June and 1 September, or 1 July and 1 September. There were four different pasture mixes of bird's-foot trefoil with one other pasture plant species (such as orchardgrass *Dactylis glomerata*) plus a bird's-foot trefoil monoculture treatment. Plots (11 x 5 m) were established in 1983. Insects were sampled seven times in 1984 and eight times in 1985, with five sweepnet samples/plot.

A replicated, randomized, controlled trial in 1985-1989 in Oxfordshire, UK (*5*) found plots grazed in autumn-only had similar numbers of spider (Araneae) species and individuals (3.5-5.5 species, 69-197 individuals/m^2) to those grazed in spring (3.3-5.3 species, 50-119 individuals) in 1989. An ungrazed control had 7.3-8.3 species and 111-207 individuals/m^2, while plots grazed in spring and autumn had lowest species richness and abundance (1.9-2.5 species, 16-51 individuals). Delaying mowing from spring to autumn did not have a clear effect on spider species richness or density in July over the three year period (autumn-only: 4.6-5.0 species, 69-99 individuals/m^2; spring-only: 4.2-4.7 species, 50-99 individuals). The study took place in an ex-arable field (10 ha) and on old limestone grassland. In 1985, three treatments were applied (ungrazed, short-period spring or autumn sheep grazing) replicated six times in two square 3 x 3 grids of 30 x 30 m paddocks. Spring-and-autumn grazing was applied to larger areas outside the paddocks. Spiders were sampled by suction (using D-vac) and counting webs. Suction samples were taken in various months from May to October each year.

A trial in Dumfries, UK (*6*) found no detectable difference in the ground beetle (Carabidae) community between different cutting treatments on experimentally

restored flower-rich grassland plots. A field was ploughed and sown with 17 plant species in August 1987 (five grasses, two clovers *Trifolium* spp. and 12 other flowering broadleaved species) and managed without fertilizers. Half the field was cut once each July. The other half was cut twice, in May and July. Both were grazed in autumn and winter. Ground beetles were sampled in 18 pitfall traps (laid out in two lines) in each treatment area, between April and September in 1989 and 1993.

A replicated, randomized, controlled study from 1987 to 1996 in Oxfordshire, UK (*7*) found that the predatory sheet web spider *Lepthyphantes tenuis* was approximately 2.5 and 6.5 times less abundant in cut versus uncut (control) field margins in May and July respectively. Following an early (April) cut, spider numbers in cut field margins recovered to match numbers in uncut control margins by July (around 4 spiders/m^2 in each). Recovery was less successful following a later (June) cut, with around 10 spiders/m^2 in cut field margins compared with around 15 spiders/m^2 in uncut control margins by September. Field margin treatment plots measured 2 x 50 m and were replicated around six arable fields. Spiders were counted in suction trap (D-vac) samples with data pooled from 1990, 1991, 1995 and 1996.

A replicated, randomized, controlled trial in 2003-2005 on four farms in the southwest UK (*8*) (same study as (*9*)) found that 50 x 10 m plots of permanent pasture with delayed cutting (cut in July) had similar numbers of predatory beetles (Coleoptera) and slightly more seed- or flower-feeding beetles than plots cut in May. There were similar numbers of root or stem feeding beetles and foliage feeding beetles in plots cut in May and plots cut in July. Overall beetle numbers were similar between treatments, but there were slightly more beetle species in plots cut in July (30-38 species) than cut in May (27-34 species). The study also showed that reducing the management intensity on margins (by reducing or removing fertilizer, cutting and/or grazing) increased the fraction of seed- or flower-feeding beetles in the beetle community over the three years. The study tested seven treatments: cutting in May vs July; cutting to 5 cm vs 10 cm; grazing vs no grazing; fertilizer vs no fertilizer; and a treatment with no management. Treatments were replicated 12 times.

A replicated, randomized, controlled trial in 2003-2005 on four farms in the southwest UK (*9*) (same study as (*8*)) found plots with delayed cutting (cut in July) had similar spider (Araneae), beetle (Coleoptera), true bug (Heteroptera), planthopper (Auchenorrhyncha), bumblebee (*Bombus* spp.) and butterfly (Lepidoptera) species richness to plots cut in May. Plots were 50 x 10 m on permanent pasture and were cut to 10 cm in either May or June. Each cutting treatment was replicated 12 times. Butterflies and bumblebees were monitored using transect walks, other invertebrates were monitored using a Vortis suction sampler.

A replicated study in 1997-2005 at two pastureland sites at Pustnäs and Harpsund in southern Sweden (*10*) found that delaying the start of grazing had mixed effects on different groups of insects and spiders. Ground beetles (Carabidae) were found in higher numbers in late-grazed plots (2.0-5.4 beetles/trap) compared to continuously grazed plots (1.4-3.6 beetles/trap) at Pustnäs, while at Harpsund ground beetles were more abundant in continuously grazed pasture early in the season, but became more abundant in the late-grazed plot after grazing commenced. Spiders (Araneae) were more abundant in late-

grazed plots at Pustnäs, but only until grazing started. At Harpsund, spider abundance was not affected by grazing, although some spider groups did show a response. Ant (Formicidae) numbers and diversity were higher in continuously grazed plots at Pustnäs until the start of grazing in late-grazing plots. At Harpsund there was no overall difference between treatments, although numbers of some individual species differed. The experiment used an enclosed 1 ha plot in a 2 ha pasture at Pustnäs and a 4 ha plot in a 12 ha pasture at Harpsund. The pastures were grazed from May to September with 1.2-1.8 cows/ha. Enclosed areas were ungrazed until late July.

A replicated, randomized, controlled study in 2003-2005 on four farms in the southwest UK (*11*) (part of the same study as (*8*) and (*9*)) found similar combined numbers of planthoppers (Fulgoromorpha) and leafhoppers (Cicadomorpha) in pasture cut in July (averaging approximately 580 individuals/treatment) and cut in May (620 individuals). Planthopper and leafhopper species richness was also similar with 16.1 species in July-cut plots and 15.9 species in May-cut plots. More planthoppers and leafhoppers were found when pasture was cut only once (860 individuals/treatment), or not at all (595 individuals), compared with pasture cut twice (485 individuals). Cutting took place in July (a hay cut) or in May (a silage cut to 10 cm grass height) in permanent pastures. Plots were 50 x 10 m and treatments were replicated 12 times. Planthoppers and leafhoppers were collected in April, June, July and September in each year using a Vortis suction sampler, taking 75 ten-second suction samples/plot. June and September sampling occurred at least two weeks after cutting.

(1) Morris M.G. (1979) Responses of grassland invertebrates to management by cutting: II. Heteroptera. *Journal of Applied Ecology*, 16, 417-432.
(2) Morris M.G. (1981) Responses of grassland invertebrates to management by cutting: III. adverse effects on Auchenorhyncha. *Journal of Applied Ecology*, 18, 107-123.
(3) Morris M.G. (1981) Responses of grassland invertebrates to management by cutting: IV positive responses of Auchenorhyncha. *Journal of Applied Ecology*, 18, 763-771.
(4) Mackun I.R. & Baker B.S. (1990) Insect populations and feeding damage among birdsfoot trefoil-grass mixtures under different cutting schedules. *Journal of Economic Entomology*, 83, 260-267.
(5) Gibson C.W.D., Hambler C. & Brown V.K. (1992) Changes in spider (Araneae) assemblages in relation to succession and grazing management. *Journal of Applied Ecology*, 29, 132-142.
(6) Blake R., Foster G.N., Fisher G.E.J. & Ligertwood G.L. (1996) Effects of management practices on the carabid fauna of newly established wildflower meadows in Scotland. *Annales Zoologici Fennici*, 33, 139-147.
(7) Bell J.R., Johnson P.J., Hambler C., Haughton A.J., Smith H., Feber R.E.*, et al.* (2002) Manipulating the abundance of *Lepthyphantes tenuis* (Araneae: Linyphiidae) by field margin management. *Agriculture, Ecosystems & Environment*, 93, 295-304.
(8) Woodcock B.A., Potts S.G., Pilgrim E., Ramsay A.J., Tscheulin T., Parkinson A.*, et al.* (2007) The potential of grass field margin management for enhancing beetle diversity in intensive livestock farms. *Journal of Applied Ecology*, 44, 60-69.
(9) Woodcock B.A., Potts S.G., Tscheulin T., Pilgrim E., Ramsey A.J., Harrison-Cripps J.*, et al.* (2009) Responses of invertebrate trophic level, feeding guild and body size to the management of improved grassland field margins. *Journal of Applied Ecology*, 46, 920-929.
(10) Lenoir L. & Lennartsson T. (2010) Effects of timing of grazing on arthropod communities in semi-natural grasslands. *Journal of Insect Science*, 10, 1-24.
(11) Blake R.J., Woodcock B.A., Ramsay A.J., Pilgrim E., Brown V.K., Tallowin J.R.*, et al.* (2011) Novel margin management to enhance Auchenorrhyncha biodiversity in intensive grasslands. *Agriculture, Ecosystems & Environment*, 150, 506-513.

6.2. Use grazing instead of cutting for pasture or grassland management

- **Natural enemies:** Two studies[1,2] (one before-and-after and one replicated trial) from Australia and the UK found grazing instead of cutting had mixed effects on natural enemies, with some species and groups affected on some dates but not others. One replicated study[8] from New Zealand found no effect.
- **Pests and diseases:** One[3] of five studies (including three replicated trials) from Australia, New Zealand, the UK and the USA found more pests, and two studies[1,2] found effects varied between pest groups and sampling dates. Two studies[5,8] found no effect on pests. One study[6] found no effect on disease when grazing was used in addition to cutting.
- **Pasture damage and plant survival:** One randomized study[3] found more ryegrass shoots were attacked by pests. One study[4] found lower survival of alfalfa plants but another[6] found no effect.
- **Yield:** One[4] of four randomized, replicated studies (one[5] also controlled) found lower yields and two[5,6] found no effect. One study[7] found lower ryegrass and higher clover yields, but no difference between clover varieties. Another randomized study[3] found more ryegrass shoots.
- **Crops studied** were alfalfa[1,4,6], cock's-foot[8], perennial ryegrass[2,3,5,7,8], other grasses[5] and white clover[2,7,8].

Background

Natural pest control in pastures can be affected by different methods of management and harvesting. Grazing may be less damaging to natural enemies and more suitable for some pest- or disease-resistant crop varieties than cutting. Direct effects of domestic livestock on pests (e.g. mortality by grazing and trampling) are not considered part of the natural ecosystem service of pest control but are summarized here if studies measured these effects while carrying out the intervention. The intensity of grazing and frequency of cutting are often important factors and the actions 'Reduce grazing intensity on grassland' and 'Reduce frequency of cutting on grassland or grass margins' will be covered in future synopses. Ground-living invertebrates can be sampled by suction sampling, using a vacuum to suck-up and collect specimens for a given time or area of ground.

A before-and-after trial in 1979 in lucerne *Medicago sativa* in New South Wales, Australia (*1*) found a smaller reduction in predatory adult brown lacewings *Micromus* sp. after grazing (57% decline, from 8.6 to 3.7 adults/2 m^2) than after cutting (91-94% decline, 5.1-7.0 to 0.3-0.6 adults). Numbers remained higher in grazed than cut lucerne seven days after treatment. Brown lacewing larvae declined by 82% in grazed compared to 98% in cut lucerne. Grazing and cutting caused similar declines for transverse ladybirds *Coccinella transversalis* (68% vs 78-83%, respectively). Blue-green aphids *Acyrthosiphon kondoi Shinji* declined less under grazing (70% decline, from 93 to 28 aphids/3.1 m^2) than cutting (89-90% decline, 66-113 to 6.6-12.1 aphids) but numbers were similar after seven days. Mowing, windrowing (piling cut vegetation in rows on the field) and baling lucerne before collection had little effect on pest or natural enemy

numbers compared to harvesting directly into a trailer. Treatments included grazing (84 cattle for 1 day on 0.45 ha), cutting with a forage harvester and collecting the crop immediately (0.3 ha), and mowing and windrowing before baling and collection (0.3 ha). Aphids and predators were sampled with a suction sampler at 10 random quadrat sites/treatment.

A replicated trial in perennial ryegrass *Lolium perenne* and white clover *Trifolium repens* pasture in 1976-1977 in County Kildare, Ireland (*2*) found that effects of grazing vs cutting varied between invertebrate groups and sampling dates. Fewer spiders (Araneae) occurred in continuous, lightly grazed (2-105 spiders) or intermittent, heavily grazed (2-121 spiders) plots than in cut plots (10-429 spiders/suction sample) for seven of eleven months. Wasps (Hymenoptera) showed mixed effects with fewer in continuous, lightly grazed than cut plots for three months, but the opposite for one month and no difference for seven months. In total, fewer small invertebrates occurred in grazed (13,120-17,750 invertebrates) than in cut (17,800-21,050 invertebrates/suction sample) plots during peak abundance in July-August 1977, but numbers were similar after cutting took place in September. The treatments included continuous grazing with 10-30 sheep/ha, intermittent grazing with 60-100 sheep/ha for 1-2 week periods, grass cut twice a year for silage, and two treatments combining cutting and grazing. Each treatment was tested in two 0.2 ha plots. Plant-dwelling invertebrates were sampled using a D-vac suction net in ten areas/plot (each measuring 0.09 m^2). Most natural enemy and pest groups were not differentiated.

A randomized experiment in 1980-1982 in Berkshire, UK (*3*) found more stem-boring fly (*Oscinella* spp. and *Geomyza tripuncta*) larvae in plots of grazed vs cut perennial ryegrass *Lolium perenne* (reaching peaks of approximately 3,370-5,740 vs 985-1,770 larvae/m^2) during summer and winter. Numbers were similar during late spring when adults emerged and larvae were scarce. Peak numbers of adult female flies were also higher in grazed vs cut (approximately 165-590 vs 75-150 flies/treatment) plots in both years. The study reported that more perennial ryegrass shoots were attacked by fly larvae in grazed (11-13%) than cut (7%) plots but more grass shoots also occurred in the former than the latter (45,000 vs 33,000 shoots/m^2 respectively, at peak numbers). Three plots were sheep-grazed at 28 day intervals (beginning March 1980) and each grazing event used 20 sheep for 24 hours. Three other plots were cut with a Mayfield autoscythe on the same dates as grazing events and cut material was removed. Plots were 10 x 10 m. Fly larvae were counted by dissecting grass shoots, sampled using 50 mm-diameter turf cores (five per plot) on 26 occasions over two years. Effects on natural processes of pest control were not presented.

A randomized, replicated experiment in 1977-1981 involving 22 lucerne *Medicago sativa* varieties in New South Wales, Australia (*4*) found lower yields when lucerne was grazed (average total 16,230 kg/ha over four years) rather than cut (30,893 kg/ha). Another experiment testing seven varieties found the same effect (9,740 vs 19,122 kg/ha in grazed vs cut over 3.5 years). The number of lucerne plants in grazed and cut plots declined by 89% and 51% (respectively) over four years in the first experiment and by 82% and 39% over 3.5 years in the second. Lucerne varieties that are active in winter performed better than dormant varieties when both types were grazed (9,887-11,611 vs 7,638-9,991 kg/ha yields), but yields were similar for these varieties in cut plots (16,067-

21,213 vs 19,040-20,954 kg/ha) in the second experiment. All lucerne varieties were tested in four replicate plots (10 x 2 m) divided into grazing areas of 8 x 2 m (grazed with 85 Merino sheep/ha) and cutting areas of 2 x 2 m. Grazing occurred approximately every 6 weeks and for 4-29 days each time (202-287 days in total). Yields were measured as dry vegetation matter. Effects on natural processes of pest control were not presented.

A randomized, replicated, controlled experiment in 1990-1992 on a pasture in Essex, UK (*5*) found similar grazing intensities of brent geese *Branta bernicla* (pests) on sheep-grazed plots (averaging 31.6-39.5 total goose droppings/m^2/winter), cut and grazed plots (28.2-36.4 droppings), and cut-only plots (28.5-36.8 droppings). The amount of vegetation was similar between grazed (223-236 g dry weight/m^2), cut and grazed (195-255 g/m^2) and cut-only plots (188-232 g/m^2). In another randomized, replicated, controlled experiment, grazing intensities of brent geese were similar in sheep-grazed (59.6 total droppings/m^2) and cattle-grazed (60.2 droppings/m^2) plots. In the first experiment, grazed plots contained sheep in April-May or June and July-September and grazing intensities varied from 13.5-92.2 livestock unit days. Cut and grazed plots were cut on 26 June then grazed for one or two one-month periods. Cut plots were cut in late June and late August. Each treatment was replicated six times in 100 x 75 m plots. In the second experiment six plots (of 50 x 50 m) were grazed by 14 cattle and six plots were grazed by 6-11 sheep in June-August. Goose droppings were monitored in sample areas (with 1.5 m-radiuses) at 5 and 10 random points/plot (first and second experiments, respectively).

A randomized, replicated experiment in 1986-1988 in Wyoming, USA (*6*) found similar alfalfa *Medicago sativa* yields in plots cut twice and grazed (2.6-9.8 Mg/ha) compared to plots cut three times but not grazed (2.8-9.9 Mg/ha). Plant density at the end of the experiment (1988) was similar in plots cut twice and grazed (47.5% plants remaining) and plots cut three times (43.8%). Grazing reduced yields when used in addition to cutting, for example in 1988 plots cut twice and grazed yielded 2.55 Mg/ha compared with 2.96 Mg/ha in plots cut twice only, while plots cut three times and grazed yielded 2.31 Mg/ha compared with 2.78 Mg/ha in plots cut three times only. In another experiment, grazing in addition to cutting did not affect Verticillium wilt severity (caused by *Verticillium albo-atrum*), alfalfa yield or plant density in wilt-resistant and wilt-susceptible alfalfa varieties. The first experiment compared plots cut twice, cut twice and grazed in autumn, cut three times, and cut three times and grazed in autumn. Each treatment was replicated four times in 3.7 x 3.7 m plots. Plots were grazed after the first autumn frost (5 cows/ha). The second experiment tested the same treatments plus two alfalfa varieties.

A randomized, replicated experiment in 2001-2004 in a mixed perennial ryegrass *Lolium perenne* and white clover *Trifolium repens* pasture in Aberystwyth, UK (*7*) found higher perennial ryegrass yields under grazing (770-2,312 kg/ha in 2002-2003) compared to cutting (171-1,083 kg/ha) regimes on most dates in two experiments. White clover yields were lower under grazing (111-1,352 kg/ha) than cutting (247-1,430 kg/ha) regimes on most sampling dates, but total yields (ryegrass and clover) were higher with grazing. Grazing did not improve the performance of a nematode-resistant white clover variety compared to a conventional variety (yields of 94-1,412 vs 98-1,266 kg/ha

respectively when grazed; 512-1,442 vs 264-1,334 kg/ha when cut). Two experiments tested the effects of sheep grazing (April-October) vs cutting six times/year, as well as using two white clover varieties (both individually and mixed together). One experiment was conducted under natural conditions (results were not presented) while the other supplemented the pasture with plants artificially infested with pest stem nematodes *Ditylenchus dipsaci*. Twelve plots of 5 x 4 m were subdivided into grazing (3.5 x 4 m) and cutting (1.5 x 4 m) areas. Yield samples measuring dry vegetation matter were taken on all cutting dates for three years (2002-2004).

A replicated study in 2002-2007 in Taranaki, New Zealand (*8*) found similar numbers of predatory and omnivorous (plant and animal-eating) nematodes (Nematoda) in grazed (approximately 6,000-30,000 individuals/m^2) and cut (10,000-50,000 individuals) pasture. Numbers of small predatory invertebrates, including mites (Acari), beetles (Coleoptera), spiders (Araneae) and other groups, were also similar in grazed vs cut plots (4,000-20,000 vs 7,000-24,000 individuals/m^2). Numbers of plant-feeding or plant-parasitic nematodes were similar between grazed vs cut plots, for example 7,700-53,900 vs 9,000-23,400 *Pratylenchus* spp. individuals/m^2 and 0-99,200 vs 4,700-13,000 *Meloidogyne* spp. juveniles/m^2 in up to 10 cm-deep soil samples. Numbers of plant-eating small invertebrates, including mites, springtails (Collembola), beetle larvae, moths and butterflies (Lepidoptera), were also similar in grazed vs cut plots (600-5,500 vs600-7,000 individuals/m^2). Grazed plots were stocked at 3, 4 or 5 cows/ha. Pasture was mown and vegetation was removed in cut plots. Each treatment was applied to four 0.1 ha plots. Measurements were taken in 2007 after five years of treatment. Invertebrates were sampled using soil cores (up to 15.5 cm deep) in autumn and winter. Natural enemies and pests were not differentiated in many invertebrate groups.

(1) Bishop A.L., Greenup L.R. & Holtkamp R.H. (1980) Management of *Acyrthosiphon kondoi Shinji*, blue-green aphid, and *Therioaphis trifolii* (Monell) f. *maculata*, spotted alfalfa aphid, by grazing and cutting lucerne. *Australian Journal of Experimental Agriculture and Animal Husbandry*, 20, 710-716.

(2) Purvis G. & Curry J.P. (1981) The influence of sward management on foliage arthropod communities in a ley grassland. *Journal of Applied Ecology*, 18, 711-725.

(3) Moore D. & Clements R.O. (1984) Stem-borer larval infestation of ryegrass swards under rotationally grazed and cut conditions. *Journal of Applied Ecology*, 21, 581-590.

(4) Lodge G.M. (1985) Effects of grazing and haycutting on the yield and persistence of dryland aphid-resistant lucerne cultivars at Tamworth, New South Wales. *Australian Journal of Experimental Agriculture*, 25, 138-148.

(5) Vickery J.A., Sutherland W.J. & Lane S.J. (1994) The management of grass pastures for brent geese. *Journal of Applied Ecology*, 31, 282-290.

(6) Gray F.A. & Koch A.W. (2004) Influence of late season harvesting, fall grazing, and fungicide treatment on Verticillium wilt incidence, plant density, and forage yield of alfalfa. *Plant Disease*, 88, 811-816.

(7) Williams T.A., Abberton M.T., Olyott P., Mizen K.A. & Cook R. (2007) Evaluation of the effects of resistance to stem nematode (*Ditylenchus dipsaci*) in white clover (*Trifolium repens* L.) under sheep grazing and cutting. *Plant Breeding*, 126, 343-346.

(8) Schon N.L., Mackay A.D., Yeates G.W. & Minor M.A. (2010) Separating the effects of defoliation and dairy cow treading pressure on the abundance and diversity of soil invertebrates in pastures. *Applied Soil Ecology*, 46, 209-221.

6.3. Grow plants that compete with damaging weeds

- **Weed weight and cover:** Nine studies[1,2,3,4,5,6,7,8,9] from Australia, Slovakia, the UK and the USA tested the effects of planting species to compete with weeds. All (including four replicated, randomized, controlled trials) found reduced weed plant weight or ground cover, although two[2,4] found this only in some years or conditions.
- **Weed reproduction and survival:** Five studies[2,3,5,6,8] (including three replicated, randomized, controlled trials) also found that competition reduced weed reproduction, survival or both. One of these[2] found an effect only in one year only.
- **Crops studied** were clovers[9], fescues[1,2,4], ryegrass[6], other grasses[3,4,5,7,8,9] and turnip[5].

Background

This action involves planting species that out-compete damaging weeds, suppressing them by reducing their ground cover, growth or reproduction rate, or by increasing their mortality. The action is generally applied to pastureland or uncropped areas such as field margins and buffer strips. Plants grown to suppress weeds on large parts of arable land are not included here but are relevant to cover cropping actions, e.g. 'Grow cover crops when the field is empty', 'Grow cover crops beneath the main crop (living mulches) or between crop rows', 'Grow crops in strips within a cover crop' and 'Incorporate leys into crop rotation' (actions for inclusion in a future synopsis).

Here we present evidence from nine of 13 studies testing this action.

A randomized, replicated trial in fallow farmland in Virginia, USA (*1*) found that sowing plots with tall fescue *Festuca arundinacea* and crownvetch *Coronilla varia* at recommended rates reduced shoot weight of the weed creeping thistle *Cirsium arvense* by 96%, compared to plots with no competitor plants. Sowing competitor plants at half or double the recommended rate reduced thistle shoot weight by 84-85% and 85-86% respectively. Length and weight of thistle roots followed similar patterns. Average thistle shoot weight increased from the first to the second year of competition (6.7 vs 44.3 g/plot), but decreased after three years of competition (11.5 g/plot). Plots were 2 x 2 m separated by 1 m, in four replicate blocks. Each block had 12 randomized treatments: 0, 0.5, 1 and 2 times the recommended sowing rate (50 and 20 kg/ha of tall fescue and crownvetch respectively) for one, two or three years. The study was part of a biological control experiment using the thistle-eating green tortoise beetle *Cassida rubiginosa*, which was maintained at a density of >50 adults/m^2. Numbers quoted were extracted from figures and converted from logarithms.

A randomized, replicated trial in farmland in Virginia, USA (*2*) found that sowing plots with tall fescue *Festuca arundinacea* and crownvetch *Coronilla varia* reduced shoot weight (0.1-2.7 g/plant vs 0.0-6.0 g/plant in control plots), reproduction (0.1-1.3 vs 0.0-2.9 plants produced/original plant) and survival (0.0-1.6 vs 0.8-2.8 plants surviving out of three) of creeping thistle *Cirsium arvense* in one year out of two. In the second year of the experiment thistle shoot weight was not affected, but plots with competitor plants had lower thistle root weight (0.0-2.6 vs 0.5-3.3 g/plant) and root length (14.9-57.0 vs 1.3-45.1 cm/plant). The experiment also found that the thistle-eating green tortoise beetle *Cassida rubiginosa* reduced thistle biomass and reproduction in both years. Plots were 8 x 10 m in blocks of two, one plot without competitor plants

and one plot with tall fescue and crownvetch sown at 50 and 20 kg/ha respectively. Thistles were planted in cages in a 2 x 2 m grid, and four treatments of 0, 5, 10 or 20 green tortoise beetles were applied randomly to three plants within each plot.

A replicated study in 1996 in a greenhouse in Queensland, Australia (*3*) found that under competition from buffelgrass *Cenchrus ciliaris*, the weed ragweed parthenium *Parthenium hysterphorus* had reduced average height (29.9 cm vs 39.8 cm in control plots), weight (1.63 vs 7.72 g/plant) and reproduction (373 vs 1880 mature seed heads/plant and 1140 vs 4970 viable seeds/plant). The experiment also found that the ragweed borer moth *Epiblema strenuana* reduced ragweed parthenium size and reproduction, and that the moth and buffelgrass competition together had a greater effect on seed head production than each did individually. Ragweed parthenium was planted in 15 pots with buffelgrass and 15 without. Two weeks after sowing, plants were thinned to one ragweed parthenium and three buffelgrass seedlings/pot. Within each set of 15 plants, five received 10 ragweed borer eggs 35 days after germination and five received 10 eggs 53 days after germination. The experiment ran for 120 days.

A replicated, controlled study in grassland in 1996-1997 in Berkshire, UK (*4*) found that percentage ground cover of the weed creeping thistle *Cirsium arvense* was reduced by 70-90% by sowing wildflower seeds on ungrazed, ploughed grassland. Sowing wildflower seeds had no effect on creeping thistle cover on undisturbed grassland, or on ploughed grassland that was grazed by rabbits *Oryctolagus cuniculus*. The results were part of a larger experiment that used five replicated blocks of forty-eight 2 x 2 m plots. Factors in the experiment were grazing (rabbits excluded or not), insecticide (applied or not), slug and snail control (applied or not), wild flower seeds (sown or not) and three disturbance treatments: control, ploughing and rotavating to 25 cm depth and ploughing and rotavating followed by fumigation with methyl bromide for seven days. Wildflower plots were sown with 60 species of wild flower at 1000 seeds/species/m^2. Rabbits were excluded with 1 m high, 3 cm mesh fencing. Quoted numbers were extracted from figures in the paper.

A randomized, replicated, controlled study in 1999 in a greenhouse in Pennsylvania, USA (*5*) found that the weed curly dock *Rumex crispus* did not grow in pots where turnip *Brassica rapa* was used as a pasture species. Curly dock plant weight was 0 g/m^2 when grown with turnip compared to 80-89 g/m^2 with other pasture species and 191 g/m^2 when grown alone. Curly dock also had a reduced germination rate when grown with turnip (19%) compared to other pasture species (31-38%) or when grown alone (60%). The experiment used 30 litre pots which each received 100 turnip or other pasture species seeds and 100 curly dock seeds. The control treatment was not sown with pasture species. Plants were harvested 65 days after planting and weight of above ground plant matter was measured for each species.

A replicated, randomized, controlled trial in a greenhouse in Tasmania, Australia (*6*) found that ryegrass *Lolium perenne* competition reduced average shoot weight of invasive gorse *Ulex europaeus* by 96%. Ryegrass competition used together with a biological control agent (gorse thrips *Sericothrips staphylinus*) or with simulated grazing also increased gorse seedling mortality by 23 and 33% respectively, and by 93% when all three were combined. However, gorse seedling mortality was not affected by ryegrass, thrips or simulated

grazing alone. Gorse seedlings were grown in boxes of six in a greenhouse at 20°C. Treatments were 1.5 g/m^2 ryegrass seeds, 10 thrips/plant and simulated grazing by cutting with scissors to 3 cm height, plus all possible combinations of these three. Each treatment was replicated five times. Seedling mortality and shoot weight after 123 days were recorded.

A randomized, replicated, controlled trial in 2005 in a greenhouse in Colorado, USA (*7*) found reduced growth of diffuse knapweed *Centaurea diffusa* (an invasive weed) when grown in competition with prairie sagewort *Artemisia frigida* (diffuse knapweed weight of 1.5 g/plant) or blue grama grass *Bouteloua gracilis* (0.5 g/plant), compared to growing diffuse knapweed alone (2.2 g/plant). Diffuse knapweed also reduced yield of prairie sagewort by 58% and of blue grama by 35% compared to growing either species alone. The experiment used 2 litre pots with one diffuse knapweed plant and two prairie sagewort or blue grama plants, and controls with each species individually. Pots containing diffuse knapweed also received one of four different treatments with herbivorous insects used for biological control. Each treatment was replicated 12 times.

A randomized, replicated, controlled study in a glasshouse (*8*) found that the weed ragweed parthenium *Parthenium hysterophorus* had 12% lower plant height, 20% lower plant weight and 22% lower seed production when grown in pots containing one buffelgrass *Cenchrus ciliaris* plant, compared to when grown without competition. Plants were grown from seed in trays, and transplanted into 20 cm diameter plastic pots after 14 days. Pots were kept in a naturally lit greenhouse with 13 hours of daylight, at 26-30°C. Competition pots had one ragweed parthenium and one buffelgrass plant, while control pots had only one ragweed parthenium. Each treatment was replicated six times, as part of a larger experiment on biological control. Plant height and weight was measured after 16 weeks. Study location and date are not given.

A controlled study in 2004-2008 in pasture land in the Strážov Hills, Slovakia (*9*) found that the proportion of pasture covered by stinging nettles *Urtica dioica* was reduced by 91% after one season of cutting and reseeding with cock's foot *Dactylis glomerata* and white clover *Trifolium repens*. Cutting without reseeding reduced stinging nettle cover by 70% if cuttings were left as a mulch, or by 51% if cuttings were removed. Stinging nettles increased by 11% in an uncut and unseeded treatment. By the end of year five of the study, stinging nettles were rare in the cut and reseeded treatment, covered 1-2% of the pasture in the cut, unseeded treatments and covered 93% of the pasture in the uncut, unseeded treatment. Grass cover in the cut and reseeded plots was 84% by the end of the second year and remained between 68-92% for the rest of the experiment, compared to 3.7-43% in the cut, unseeded treatments and 0.3-6% in the uncut, unseeded treatment. Cut plots were cut every fifth week, starting when the ground cover was 250-300 mm high. The paper gives no further details of the study set-up.

(1) Ang B.N., Kok L.T., Holtzman G.I. & Wolf D.D. (1994) Competitive growth of Canada thistle, tall fescue, and crownvetch in the presence of a thistle defoliator, *Cassida rubiginosa* Müller (Coleoptera: Chrysomelidae). *Biological Control*, 4, 277-284.

(2) Ang B.N., Kok L.T., Holtzman G.I. & Wolf D.D. (1995) Canada thistle [*Cirsium arvense* (L) Scop.] response to density of *Cassida rubiginosa* Müller (Coleoptera: Chrysomelidae) and plant competition. *Biological Control*, 5, 31-38.

(3) Navie S.C., Priest T.E., McFadyen R.E. & Adkins S.W. (1998) Efficacy of the stem-galling moth *Epiblema strenuana* Walk. (Lepidoptera: Tortricidae) as a biological control agent for ragweed parthenium (*Parthenium hysterophorus* L.). *Biological Control*, 13, 1-8.

(4) Edwards G.R., Bourdôt G.W. & Crawley M.J. (2000) Influence of herbivory, competition and soil fertility on the abundance of *Cirsium arvense* in acid grassland. *Journal of Applied Ecology*, 37, 321-334.
(5) Tracy B.F. & Sanderson M.A. (2004) Forage productivity, species evenness and weed invasion in pasture communities. *Agriculture, Ecosystems & Environment*, 102, 175-183.
(6) Davies J.T., Ireson J.E. & Allen G.R. (2005) The impact of gorse thrips, ryegrass competition, and simulated grazing on gorse seedling performance in a controlled environment. *Biological Control*, 32, 280-286.
(7) Norton A.P., Blair A.C., Hardin J.G., Nissen S.J. & Brunk G.R. (2008) Herbivory and novel weapons: no evidence for enhanced competitive ability or allelopathy induction of *Centaurea diffusa* by biological controls. *Biological Invasions*, 10, 79-88.
(8) Fauzi M.T. (2009) Biocontrol ability of *Puccinia abrupta* var. *partheniicola* on different growth stages of parthenium weed (*Parthenium hysterophorus* L.). *Hayati Journal of Biosciences*, 16, 83-87.
(9) Vozár L., Jančovič J. & Bačová S. (2009) Regulation of *Urtica dioica* L. on grasslands. *Proceedings of the Alternative Functions of Grassland. 15th European Grassland Federation Symposium, 7-9 September 2009*. Brno, Czech Republic, Vol. 14, pp 559-562.

6.4. Use mixed pasture

- **Weeds:** Two of two studies (randomized and replicated and one also controlled) from the USA[5,6] found weeds were negatively affected by mixed compared to monoculture pasture.
- **Pests:** Five studies[1,2,3,5,7] from North America measured pests including four randomized, replicated, controlled tests. One study[5] found fewer pests and two studies[2,3] found negative or mixed effects depending on different pests groups or pasture mixes. One study[7] found no effect and another[1] found more pests, although the effect was potentially inseparable from grazing treatments.
- **Crop mortality:** One randomized, replicated study[4] from the USA found no effect on forage crop mortality caused by nematodes.
- **Yield:** Two[1,6] of five studies (including two randomized, replicated, controlled tests) from North America found increased forage crop yields and two studies[4,5] found mixed effects depending on the crop type and year. One study[2] found no effect.
- **Crops studied** are alfalfa[1,3,5,7], bird's-foot trefoil[2,6], chicory[6], cicer milkvetch[1], clovers[5,6], fescues[2,6], oats[5], plantain[6], ryegrass[2,6], other grasses[2,3,4,5,6,7], other legumes[4], rapeseed[6] and turnip[6].

Background

This involves growing more than one species of forage crop (grasses and legumes) in a pasture to control invertebrate or weed pests in pastoral farmland. The use of mixed pastures to suppress pests in arable crops is not included here but relevant to other actions, e.g. 'Include plants that are repellent or suppressive to pests in crop rotations' and 'Grow cover crops that are repellent or suppressive to pests when the field is empty' (for inclusion in a future synopsis).

Here we present evidence from seven of 10 studies testing this action.

A replicated, controlled trial from 1982-1985 at two pasture sites in Montana, USA (*1*) found that an index of overall grasshopper (Orthoptera) grazing intensity and presence was higher in interseeded pastures (19-2,852 grasshopper days/m^2) than control native pasture (7-1,377 days/m^2) but annual

rates of grasshopper increase were similar between treatments (5.35x vs 5.92x annual increase). One dominant species, the migratory grasshopper *Melanoplus sanguinipes* increased more in interseeded plots (29-1,367 estimated cumulative grasshopper days/m^2) than controls (23-501 days/m^2) from 1983-1985. Grasshoppers caused 10% seedling mortality in one interseeded plot. Forage yield was higher in interseeded (454-1,290 kg/ha total herbaceous yield) than control pastures (240-739 kg/ha). Two pastures (one at each site) were seeded with dryland alfalfa *Medicago falcata* and cicer milkvetch *Astragalus cicer* (both at 2.2 kg/ha) in April-May 1982. One was treated with herbicide, the other cut mechanically to control sagebrush *Artemesia tridentata* (weed). Control pastures had a mix of unsown species. Interseeded pastures were grazed by 10 steers for 48, 40 and 20 days and control pastures by five steers for 90, 60 and 40 days in 1983-1985 respectively. The effects of interseeding and different grazing intensities could not be separated.

A randomized, replicated, controlled trial in 1984-1985 at two sites in West Virginia, USA (*2*) found that pest insect numbers varied between monoculture pasture and mixed pasture. Spittlebug (Cercopidae) nymphs were significantly more abundant in mixed pastures of bird's-foot trefoil *Lotus corniculatus* with either perennial ryegrass *Lolium perenne* or orchardgrass *Dactylis glomerata* than in a bird's-foot trefoil monoculture. Mirid (Miridae) nymphs were significantly less abundant on two types of mixed pasture than monoculture. The ryegrass and bird's-foot trefoil mix had the highest numbers of adult and nymph leafhoppers and planthoppers (Cicadellidae and Delphacidae), mirids and aphids (Aphididae) compared to other mixes and bird's-foot trefoil monoculture. Forage yields were not different between the different pasture types. There were five pasture mixtures: bird's-foot trefoil monoculture (15 kg/ha) or 10 kg/ha bird's-foot trefoil plus: orchardgrass (4 kg/ha), timothy *Phleum pratense* (4 kg/ha), perennial ryegrass (10 kg/ha) or tall fescue *Festuca arundinacea* (6 kg/ha). Plots (11 x 5 m) were established in 1983. Insects were sampled seven times in 1984 and eight times in 1985, with five sweepnet samples/plot.

A randomized, replicated, controlled study of mixtures of alfalfa *Medicago sativa* and meadow grasses in 1990-1991 at two sites in Michigan, USA (*3*) found 22-30% fewer adult potato leafhoppers *Empoasca fabae* in an alfalfa-smooth bromegrass *Bromus inermis* mix and 22-48% fewer leafhoppers in an alfalfa-orchardgrass *Dactylis glomerata* mix compared with alfalfa monocultures. Alfalfa mixed with timothy *Phleum pratense* showed both slight reductions (4-5%) and increases (1-5%) when seeded at 4.5 kg/ha. There were eight treatments: alfalfa-only at 18 or 14.6 kg/ha, alfalfa at 14.6 kg/ha with: smooth bromegrass at 5.6 or 2.8 kg/ha, orchardgrass at 1.1 or 0.6 kg/ha, timothy at 4.5 or 2.2 kg/ha. Plots (9.9 x 12.2 m) were established in 1989. There were 4-5 replications at both sites. Plots were harvested twice in 1989 and three times in the following years. Potato leafhoppers were sampled using a D-vac suction sampler after the first and second cuts.

A series of two laboratory experiments and one randomized, replicated field trial from 1990-1992 in Wyoming, USA (*4*) found no difference in mortality caused by the northern root knot nematode *Meloidogyne hapla* for plants in mixed pasture (sainfoin *Onobrychis viciifolia* and meadow brome *Bromus riparius*) compared to monoculture pasture. Sainfoin had 26.6-90.0% nematode-caused mortality in monoculture and 26.7-98.3% when intercropped. Meadow

brome (the species used as intercrop) had 0-16.7% mortality in monoculture and 0% mortality in intercropping. Total sainfoin mortality was 70.8-98.3% in monoculture and 91.7-100% in intercropping. Sainfoin shoot and root biomass were consistently higher in monoculture (shoot: 0.04-0.51 g dry weight/plant; root: 0.02-1.8) than intercropping (shoot: 0.00-0.01; root: 0.00-0.01). Meadow brome had higher shoot and root biomass in intercropping (shoot: 1.0-2.97 g dry weight/plant; root: 1.6-5.83) than monoculture (shoot: 3.5-36.2; root: 5.9-76.6). In the field experiment, forage yields were higher in intercropping (34.27 and 37.01 t dry matter/ha) than monocropped sainfoin (13.08-15.39) but lower than monocropped meadow brome (44.28). Plants in the laboratory experiments were grown in pots of pasteurized soil inoculated with 5,000 nematode eggs/l soil in a glasshouse or growth chamber.

A randomized, replicated, controlled trial in 1994-1997 on plots of alfalfa *Medicago sativa* in California, USA (*5*) found fewer Egyptian alfalfa weevil *Hypera brunneipennis* larvae in mixed alfalfa pastures (2.7-9.5 weevils/sweep) than in alfalfa-only plots (5.5-12.2 weevils/sweep) in all three years. Total forage yield for the first four harvests of each year was higher in 1994-1995 in alfalfa mixed with either berseem clover *Trifolium alexandrinum* or oats *Avena sativa* and similar between monoculture and mixed pasture plots in 1995-1996 and 1996-1997. The density of weeds was generally lower in mixed pastures than alfalfa-only pasture over all three years. The alfalfa plots had been established for 2-5 years. Plots were replicated six times in 1994-1995 (plots 3.6 x 9 m) and 1995-1996 (3.6 x 14 m) and three times in 1996-1997 (16 x 30 m). The plots were lightly harrowed and sown with either berseem clover, oats, orchardgrass *Dactylis glomerata* or red clover *Trifolium pratense* in October each year. Ten sweep net samples were taken in each plot.

A randomized, replicated trial in 1998-2000 in pasture land in Pennsylvania, USA (*6*) found that weed density was lower in plots with a higher diversity of pasture species. Total weight of weed plant material was generally lower in plots with six or more species. Pasture species yield was higher in plots with lower weed density. An additional randomized, replicated, controlled greenhouse trial in 1999 found that plant weight of the weed curly dock *Rumex crispus* was lower when grown with a mix of 10 pasture species (1-10 g/m^2) than with one or five species (75-89 g/m^2), except when the single species was turnip *Brassica rapa* which completely suppressed the weed (see 'Plant species that compete with damaging weeds'). The field trial used 2.25 m^2 plots with eight pasture species mix treatments of 1-15 species, replicated 12 times. Each plot received 120 g of seed divided equally between the pasture species. The greenhouse trial used 30 litre pots, each of which received 100 curly dock seeds and 100 pasture species seeds divided equally between species in six species mix treatments with one, five or 10 species. Control pots received no pasture species seeds. Each treatment was replicated six times.

A randomized, replicated, controlled trial in 2004 in Saskatchewan, Canada (*7*) found the total number of nematodes (Nematoda) and nematode diversity in the top soil layer was significantly higher in plots of mixed pasture than monoculture. There were 901 nematodes/100 g dry soil in mixed pasture compared to 681 in monoculture. Fungus-feeding (199 vs 170 nematodes) and omnivorous (380 vs 100) nematodes were significantly more abundant in mixed pasture than monoculture. The number of plant parasitic nematodes was not

significantly different in mixed pasture than monoculture (48 vs 30 nematodes/100 g). There were two treatments in four blocks: alfalfa *Medicago sativa* monoculture and mixed pasture of alfalfa and Russian wildrye *Psathyostachys juncea*. Plots were 1.8 x 6 m, established in 1997 and seeded at 25 seeds/30 cm in 30 cm-wide rows. Two 5 cm-diameter samples of the top 7.5 cm soil layer were taken in each plot, on three occasions (30 June, 1 and 30 September). Nematodes were extracted using the sieving-Baermann funnel technique.

(1) Hewitt G.B. & Onsager J.A. (1988) Effects of sagebrush removal and legume interseeding on rangeland grasshopper populations (Orthoptera: Acrididae). *Canadian Entomologist*, 120, 753-758.

(2) Mackun I.R. & Baker B.S. (1990) Insect populations and feeding damage among birdsfoot trefoil-grass mixtures under different cutting schedules. *Journal of Economic Entomology*, 83, 260-267.

(3) Roda A.L., Landis D.A. & Coggins M.L. (1997) Forage grasses elicit emigration of adult potato leafhopper (Homoptera: Cicadellidae) from alfalfa-grass mixtures. *Environmental Entomology*, 26, 745-753.

(4) Shigaki T., Gray F.A., Delaney R.H. & Koch D.W. (1998) Evaluation of host resistance and intercropping for management of the northern root-knot nematode in sainfoin, *Onobrychis viciifolia*. *Journal of Sustainable Agriculture*, 12, 23-39.

(5) Putnam D.H., Long R., Reed B.A. & Williams W.A. (2001) Effect of overseeding forages into alfalfa on alfalfa weevil, forage yield and quality. *Journal of Agronomy and Crop Science*, 187, 75-81.

(6) Tracy B.F. & Sanderson M.A. (2004) Forage productivity, species evenness and weed invasion in pasture communities. *Agriculture, Ecosystems & Environment*, 102, 175-183.

(7) Atul N., Hamel C., Forge T., Selles F., Jefferson P.G., Hanson K.*, et al.* (2008) Arbuscular mycorrhizal fungi and nematodes are involved in negative feedback on a dual culture of alfalfa and Russian wildrye. *Applied Soil Ecology*, 40, 30-36.

7. Annex 1: Complete list of natural pest control actions

		Num. of studies
REDUCING AGRICULTURAL POLLUTION		
Pesticides and herbicides		
1	Reduce pesticide use *	404
2	Use more selective pesticides	225
3	Provide refuges from spraying for natural enemies	2
4	Leave headlands in fields unsprayed (conservation headlands)	8
5	Use chemical application techniques that reduce the impact on natural enemies	30
6	Use pesticides only when pests or crop damage reach threshold levels *^	29
7	Incorporate parasitism rates when setting thresholds for insecticide use ^	1
8	Alter the timing of insecticide use *^	13
9	Reduce herbicide use *	108
10	Delay herbicide use ^	4
11	Avoid using genetically modified insecticidal or herbicide-resistant crops	48
Fertilizers		
12	Reduce mineral fertilizer use *	266
13	Use organic rather than mineral fertilizers	90
Reducing chemicals in general		
14	Reduce pesticide, herbicide or fertilizer use generally (including integrated management methods) *	182
15	Convert to organic farming *^	82
ALL FARMING SYSTEMS		
Manage habitat and food		
16	Grow plants that provide nectar or pollen resources	128
17	Grow plants that provide supplementary prey for natural enemies	22
18	Grow plants that provide shelter, habitat or other resources for natural enemies *	106
19	Provide grass buffer strips/margins around arable or pasture fields *	31
20	Provide refuges for natural enemies	8
21	Use alley cropping ^	10
22	Plant new hedges ^	6
23	Include short rotation coppice in the agricultural landscape	2
24	Provide supplementary food for natural enemies	7
25	Use mass-emergence devices to increase natural enemy populations ^	1
Manage crops		
26	Increase whole-farm crop diversity	4
27	Plant more than one crop per field *	570
28	Change the density at which crops are planted	171
29	Use grafting to combine different crop varieties	6
30	Use crop varieties with different timings or rates of growth	29
31	Use crop varieties that resist or suppress pests, diseases or weeds *	383

32	Induce plant defences against pests and pathogens	59
33	Apply organic liquids (e.g. crop and compost extracts) to crop foliage	33
34	Add mulch to crops *	216
35	Reduce tillage *	375
36	Reduce mechanical weed control	74
37	Leave part of the crop or pasture unharvested or uncut ^	12
38	Reduce frequency of cutting on pasture, grassland or grass margins	23
39	Alter irrigation regime	129
Control insect distribution		
40	Plant and manage trap crops to attract pests away from crop	176
41	Use crop types and varieties that attract natural enemies or enhance their effectiveness	21
42	Grow non-crop plants that produce chemicals that attract natural enemies *^	6
43	Use chemicals to attract natural enemies ^	15

ARABLE FARMING

Manage habitat		
44	Create uncropped field margins or plots by allowing natural regeneration *	25
45	Create beetle banks ^	18
46	Provide bird perches in fields	4
Manage crops		
47	Intercrop with plants that are repellent or suppressive to pests or weeds *	128
48	Grow one crop using a mixture of varieties within a field	6
49	Use crop rotation *^ [1]	252
50	Include plants that are repellent or suppressive to pests in crop rotations	62
51	Incorporate fallow periods into crop rotation	75
52	Incorporate leys into crop rotation	24
53	Use relay intercropping	8
54	Grow cover crops when the field is empty	83
55	Grow cover crops that are repellent or suppressive to pests when the field is empty	22
56	Grow crops in strips within a cover crop	3
57	Grow cover crops beneath the main crop (living mulches) or between crop rows *	103
58	Leave overwinter stubbles	1
59	Reduce burning of crop remains	15
60	Alter timing of sowing or harvesting	445
Control insect distribution		
61	Combine trap and repellent crops in a push-pull system ^	13
Soil mulch and amendments		
62	Mulch with plants that produce pesticidal fumes as they decay (such as mustard)	9
63	Incorporate pesticidal plant material into the soil	70
64	Incorporate plant remains into the soil that produce weed-controlling chemicals ^	10
65	Amend the soil with fresh plant material or crop residues	62
66	Amend the soil with crops grown as green manures	99

67	Amend the soil with processed plant materials	132
68	Amend the soil with manures and agricultural composts	227
69	Amend the soil with organic processing wastes or their composts	93
70	Amend the soil with municipal wastes or their composts	44
71	Amend the soil with composts not otherwise specified	126
72	Amend the soil with non-chemical minerals and mineral wastes	16
73	Amend the soil with formulated chemical compounds	39
74	Amend the soil with materials not otherwise specified	45

PERENNIAL FARMING

Manage crops and ground cover

75	Allow natural regeneration of ground cover beneath perennial crops ^	13
76	Grow cover crops under perennial tree crops	50
77	Cut cover crops and place in perennial tree crops to move natural enemies into the canopy	2
78	Grow pest-suppressive crops prior to planting perennial crops	1

Manage ants

79	Exclude ants that protect pests ^	8
80	Isolate colonies of beneficial ants ^	1

LIVESTOCK FARMING AND PASTURE

Livestock breeds

81	Use resistant livestock breeds	1

Manage pastures

82	Restore or create low-input grassland	0
83	Reduce management intensity on pasture or permanent grassland	4
84	Reduce grazing intensity on pasture or grassland	44
85	Delay mowing or first grazing date on pasture or grassland ^	11
86	Raise mowing height on pasture or grassland	4
87	Use grazing instead of cutting for pasture or grassland management ^	8
88	Cut noxious weeds to increase disease incidence	2
89	Grow plants that compete with damaging weeds ^	13
90	Use mixed pasture ^	10

Modify housing conditions

91	Modify flooring in poultry houses to benefit natural enemies	3

Manage disease hosts

92	Cull wildlife hosts of livestock disease	7

* Featured in the top 10 actions as chosen by groups of experts in a replicated workshop exercise to prioritize the complete list. These actions were chosen by at least one of four groups.
^ Summarized in this synopsis.
[1] Adapted to 'Use crop rotation in potato farming systems' for this synopsis.

8. Annex 2: Search terms used for gathering studies

The search equation for obtaining studies from CAB Abstracts (and secondarily the Web of Science) combined three refined search strings. Studies were selected when at least one term from each of the three strings (descriptors (DE) or topics (TO)) was found in (search equation = String 1 AND String 2 AND String 3).

Search String 1: Natural Enemies and Pests
This string combines the list of scientific genus names of pests OR a list of natural enemies as defined by broad categories.

1a.	DE=(predatory insects OR predatory arthropods OR predatory birds OR predatory mites OR natural enemies OR predators OR Biological control agent OR pest OR predator prey relationships OR pests)
OR	
1b.	TO=(*Acalitus* OR Acanthoscelides OR AcidiaOR Aclypea OR Acrolepiopsis OR Aculops OR Aculus OR Acyrthosiphon OR Adoxophyes OR Aegeria OR Aglaope OR Agriotes OR Agromyza OR Agrotis OR Aleurolobus OR Aleurothrixus OR Anarsia OR Anthonomus OR Aonidiella OR Aphanostigma OR Aphelenchoides OR Aphelenchus OR Aphidula OR Aphis OR Apion OR Apodemus OR Arammichnus Archips OR Argyrotaenia OR Arion OR Aspidiotus OR Athalia OR Atomaria OR Aulacaspis OR Aulacorthum OR Autographa OR Bemisia OR Blaniulus OR Blitophaga OR Brachycaudus OR Brachycorynella OR Brevicoryne OR Bruchus OR Byturus OR Cacoecia OR Cacopsylla OR Calepitrimerus OR Capitophorus OR Capnodis OR Capua OR Carduelis OR Cecidophyes OR Cecidophyopsis OR Ceratitis OR Ceroplastes OR Ceuthorhynchus OR Chaetosiphon OR Chromaphis OR Chrysomphalus OR Cirphis OR Clysia OR Cnephasia OR Coenorhinus OR Colaspidema OR Coleophora Colomerus Columba OR Conorhynchus OR Contarinia OR Coroebus OR Corvus OR Corylobium OR Cossus OR Crioceris OR Cryptomyzus OR Curculio OR Cydia OR Dactylosphaera OR Dacus OR Dasineura OR Delia OR Deroceras OR Dialeurodes OR Ditylenchus OR Dysaphis OR Dysaulacorthum OR Empoasca OR Eotetranychus OR Epidiaspis OR Eriophyes OR Eriosoma OR Eulecanium OR Euparypha OR Euphyllura OR Eupoecilia OR Eurydema OR Euxoa OR Euzophera OR Forficula OR Frankliniella OR Fringilla OR Geoktapia OR Globodera OR Gortyna OR Grapholitha OR Gryllotalpa OR Gymnoscelis OR Haltica OR Haplodiplosis OR Haplothrips OR Hapsidolema OR Harpalus OR Hedya OR Helicoverpa OR Heliothis OR Helix OR Heterodera OR Homoeosoma OR Hoplocampa OR Hyalopterus OR Hylemyia OR Hypera OR Hyperomyzus OR Hypoborus OR Hyponomeuta OR Icerya OR Jacobiasca OR Kakothrips OR Korscheltellus OR Laspeyresia OR Lepidosaphes OR Leptinotarsa OR Leptohylemyia OR Lepus OR Leucoptera OR Limothrips OR Liothrips OR Liriomyza OR Lobesia OR Lycophotia OR Lyonetia OR Macrosiphum OR Mamestra OR Melanaphis OR Melanchra OR Meligethes OR Meloidogyne OR Melolontha OR Metatetranychus OR Metopolophium OR Metriochroa OR Micractis OR Microtus OR Monostira OR Mythimna OR Mytilococcus OR Myzocallis OR Myzus OR Nasonovia OR Oberea OR Oecophyllembius OR Operophtera OR Ophiomyia OR Ophonus OR Oryctolagus OR Oscinella OR Ostrinia OR Otiorhynchus OR Oulema OR Palomena OR Palpita OR Pammene OR Pandemis OR Panonychus OR Parahypopta OR Parus OR Passer OR Passerinia OR Pegomyia OR Pemphigus OR Peribatodes OR Phasianus OR Philophylla OR Phloeotribus OR Phorbia OR Phorodon OR Phthorimaea OR Phyllocoptes OR Phyllonorycter OR Phyllotreta OR Phytocoptella OR Phytometra OR Phytonemus OR Phytonomus OR Phytoptus OR Pica OR Pieris OR Platyparea OR Plutella OR Polia OR Polyphylla OR Pratylenchus OR Prays OR Prolasioptera OR Protrama OR Pseudaulacaspis OR Psila OR Psylliodes OR Pyrrhula OR Quadraspidiotus OR Radopholus OR Resseliella OR Rhagoletis OR Rhopalosiphum OR Rhynchites OR Ruguloscolytus OR Saissetia OR Scaphoideus OR Scotia OR Scrobipalpa OR Scutigerella OR Sesamia OR Sitobion OR Sitodiplosis OR Sitona OR Sparganothis OR Spilonota OR Spodoptera OR Stephanitis OR

	Stigmella OR Sturnus OR Sus OR Synanthedon OR Talpa OR Tetranychus OR Thrips OR Tipula OR Toxoptera OR Trialeurodes OR Trichodorus OR Tylenchulus OR Vasates OR Vespa OR Vesperus OR Vespula OR Viteus OR Xiphinema OR Xyleborus OR Yponomeuta OR Zabrus OR Zeuzera OR Zophodia)

Search String 2: Actions

2a.	DE=(Companion crops OR Farming systems OR grassland* OR Border effects OR forest borders OR Intercropping OR crop management OR cropping systems OR crop establishment OR habitats OR territory OR biotopes OR hedges OR Landscape OR land use OR fallow OR strip* OR linear plantations OR shelterbelts OR ground cover OR trap crops OR Tillage OR agricultural land OR interspecific competition OR grazing OR cultural control)
OR	
2b.	TO=("Banker plant* system*" OR "companion vegetation*" OR "companion plant* " OR "Buffer width*" OR "buffer zone*" OR corridor* OR "field margin*" OR farmscaping OR "integrated production" OR "repellent plant*" OR "spatial arrangement*" OR "set-aside" OR "set aside" OR refuge OR Compost* OR "integrated crop management" OR habitat OR "crop system" OR groundcover OR "flowering borders" OR landscape OR interplanting

Search String 3: Outcomes

3.	TO=((increas* OR decreas* OR declin* OR regulat* OR impact* OR variabilit* OR reduc* OR effect* OR intensit* OR sustain* OR maintain* OR support* OR chang* OR enhanc* OR affect* OR abundance) SAME (abundance OR "population size" OR presence OR "species richness" OR "species diversity" OR biocontrol OR "pest control"))