PROPOSED TESTING AND USE OF CONFOUND SBW FOR THE MATING DISRUPTION OF EASTERN SPRUCE BUDWORM IN NEWFOUNDLAND AND LABRADOR

AN INTERGRATED PEST MANANGEMENT TREATMENT OF THE EARLY INTERVENTION STRATEGY USED TO MANAGE THE CURRENT OUTBREAK OF EASTERN SPRUCE BUDWORM IN THE PROVINCE OF NEWFOUNDLAND AND LABRADOR

Submission to:

DEPARTMENT OF ENVIRONMENT, CLIMATE CHANGE AND MUNICIPALITIES
ENVIRONMENTAL ASSESSMENT DIVISION

by:

DEPARTMENT OF FISHERIES, FORESTRY & AGRICULTURE
FORESTRY AND WILDLIFE BRANCH
FOREST ENGINEERING & INDUSTRY SERVICES DIVISION

April 2021

NAME AND ADDRESS OF PROPONENT

This application is submitted on behalf of

DEPARTMENT OF FISHERIES, FORESTRY & AGRICULTURE
FORESTRY AND WILDLIFE BRANCH
FOREST ENGINEERING & INDUSTRY SERVICES

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THE UNDERTAKING

In fulfilment of the mandate and commitment of the Department of Fisheries, Forestry and Agriculture (FFA) - Forestry and Wildlife Branch to protect the Provinces forest resources and ecosystem from significant impacts from native and invasive forest pests with due regard to human health and non-target environmental effects, and as a partner in the Spruce Budworm Early Intervention Strategy Phase II, the following undertaking is proposed.

Figure 1. Spruce budworm larva and defolation and mortality.

NATURE OF PROPOSED APPLICATION

As a part of the Spruce Budworm Early Intervention Strategy the Province treated ~32,000 hectares of forestland on the northern peninsula in July of 2020 with one or more applications of the biological control agent BTK, which has been approved for operational use by Health Canada – Pest Management Regulatory Agency. To learn more about last years treatment program please visit the Departments website (https://www.gov.nl.ca/ffa/programs-and-funding/forestry-programs-and-funding/idc/) (see map in attachments) where eastern spruce budworm (SBW) populations are currently on the rise and reached population thresholds where treatments under an early intervention strategy (EIS) could be conducted. The SBW is a major native forest pest that feeds on the foliage of spruce and fir with repeated defoliation causing growth loss and tree mortality. In the past, aerial treatments using chemical and biological insecticides were conducted to control SBW populations and reduce impacts/damage during an outbreak. The SBW EIS is a new strategy that has been tested over the last 7-years in the Province of New Brunswick with support from academia, industry, and the federal and provincial governments. This strategy is very different from the foliage protection strategy used in the past in that it identifies and targets areas where SBW populations are beginning to rise with the goal of knocking populations back down to levels where natural controls (i.e. predators, parasites, disease) can once again keep them in check. To date this appears to have been accomplished using control products like Btk and Mimic - these products target and cause SBW larval mortality. Various Btk and Mimic products are registered for use under Health Canada's Pest Control Product Act. In 2017, a new product called CONFOUND SBW (PCP No. 32370 – see attached) was registered for the mating disrucption of SBW. Unlike the fore mentioned products, CONFOUND SBW is a sprayable formulation of the SBW sex pheromone. The female SBW moth uses this pheromone to attract a male before mating. Pheromones produced by insects are naturally occurring compounds that are very species specific and are recognized by the OECD, PMRA, USEPA, and other regulatory organizations around the world as low-risk pesticides. When sprayed aerially over a forested area, instead of killing SBW larvae like the other products, CONFOUND SBW produces thousands of false pheromones sources in an attempt to disrupt mating of the adults. This product has been tested in the Province of New Brunswick with promising results in 2016, however, the results were not replicated. The Province would like to work with researchers from Acadia University and the Canadian Forest Service in 2021 to test and use this product to treat three 150 hectare blocks in the Whitewash Road forest access road network as part of an early intervention strategy trial.

PURPOSE OF PROPOSED APPLICATION

Background

The overall purpose of these treatments is to demonstrate and quantify the impact that CONFOUND SBW has on mating success and overall reduction of the insect population. If mating success is lowered this should result in a reduction in populations as demonstrated by a reduction in the number of overwintering SBW 2nd instar larvae (L2) found on branch samples in the fall of 2021 compared to those found on branch samples in 2020. Results in treated versus untreated areas would be evaluated to also account for natural mortality. Testing of several areas in the Province of New Brunswick in 2021 are also currently proposed and will provide additional replication of results. If these trials are successful they will not only help to reduce SBW populations, but they will also provide additional efficacy data to support the use of this new tool for the management of spruce budworm. Unlike other registered products being used under the EIS, COMFOUND SBW could potentially be used in special niche situations, i.e. in environmentally sensitive areas where these other products cannot be used. The Province would be working with researchers from Acadia University with funding for pheromone work under the AIF, as well as, with researchers from the Canadian Forestry Service conducting work under Phase II of the SBW EIS. At the end of the day the goal is to try to manage the SBW under an EIS and improve the tools and methods available. With this strategy it is also hoped that we can reduce the amount of area treated and the amount of product used to manage this important insect pest.

EASTERN SPRUCE BUDWORM

Background

As indicated the SBW is a major native forest pest defoliator. The larvae of this insect feed on the foliage of spruce and fir trees with repeated

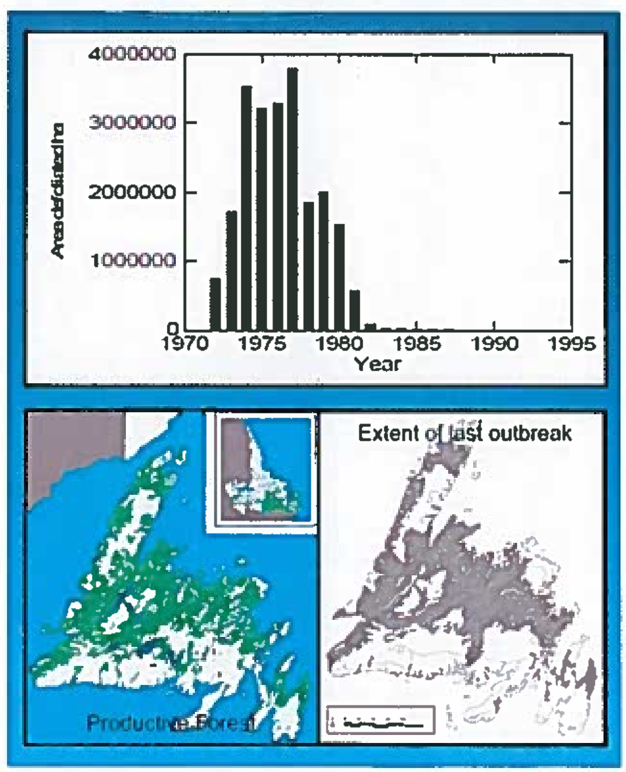


Figure 2. Time frame and extent of last SBW outbreak.

defoliation causing growth loss and tree mortality (Figure 1). Outbreaks of the SBW occur every 30-40 years. The last major spruce outbreak began in the early 1970's and ended in the mid 1980's. During this outbreak 90% of the spruce fir forests on the island were affected and 50 million cu m of wood was lost (Figure 2). At that time this volume was equal to a 25-year wood supply in the Province. Beyond impacting fiber values, the SBW can also impact other non-fiber management values (i.e. ecosystem function, forest aesthetics/recreation, habitat impacts). Hence, the importance of protecting the Provinces forests from this insect.

SBW populations have been on the rise again in Eastern Canada. The Province of Quebec is in the midst of an outbreak that began in 2005. The forest area impacted by this insect increased to 13.5 million hectares in 2020. Rising SBW populations have also been observed in northern portions of the Province of New Brunswick since 2014 and they have been actively engaged in conducting treatments under the EIS over the last 7-years with ~ 500,000 hectares of forest land treated to date. Efforts to detect rising SBW populations in Newfoundland have increased as a result of rising populations elsewhere in Eastern Canada. The spread of SBW populations appears to be aided by adult moth migration from known infested areas into new locations. Radar tracking studies have shown that these moths can be transported long distances (400-600 km) aided by weather and the right atmospheric conditions. Seventy-five to eighty percent of the adult moths found in these migration flights are females that still carry approximately half their egg compliment. These females will lay their eggs on host-trees wherever they land adding to the low or endemic populations that exist in the area (Figure 3).

Figure 3. Adult moths on small ornamental following migration.

Males in flights coming into areas with low SBW population densities can also increase mating success which in turn increases local populations. In 2013, 2018, 2019 and again 2020 increases in the number of adult moths observed on the provinces west coast has been attributed to immigration events related to moths from outside our province.

Current Situation

Pheromone trap surveys and the fall forecast results from 2020 have identified 70,000 hectares on the west coast of the island of Newfoundland with rising population SBW populations that will warrant normal control treatments are conducted under 2021 SBW EIS treatment program. Areas selected for treatment in the 2021 SBW EIS Treatment program have a minimum L2 value of 7 larvae per branch. The Department of Fisheries, Forestry and Agriculture has identified 450 hectares in the Whitewash Road area with L2 counts within the range of 4-6 larvae per branch which is considered ideal for treatment using the sex pheromone CONFOUND SBW.

It is important to note that extensive are in Gros Morne National Park and the enclaves have elevated spruce budworm populations that are of concern and that Gros Morne National Park (GMNP) is currently developing policies at a National Level related to the SBW Management. GMNP are in the middle of an intensive communication process with residents of Newfoundland and Labrador.

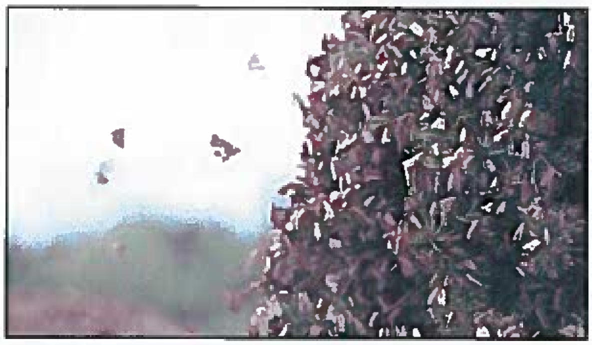


Figure 4. Area on the west coast with rising SBW populations.

Control options

As already indicated there are a number of control products (Btk, Mimic) available for conducting aerial applications to reduce SBW larval survival. Where accessibility to forest areas is difficult, aerial applications of a control product are the only practical means of control. As indicated the Province would like to work with AIF and EIS partners to conduct additional testing of CONFOUND SBW, a sprayable pheromone formulation that can be delivered using conventional spray equipment on an aircraft. If proven to be efficacious it would provide an additional and unique tool for reducing populations by interfering with mating. This product may prove valuable for use in environmentally sensitive areas or setbacks that cannot be treated with other products.

DESCRIPTION OF UNDERTAKING

Left uncontrolled, the presence of rising SBW populations on the northern peninsula could potentially lead to the spread and rise of another SBW outbreak. Given the small areas currently with rising populations, the opportunity exists to still conduct a small trial to test the efficacy of CONFOUND SBW. The Department would work closely with Acadia University, CFS, and other EIS partners to conduct this trial.

Spruce Budworm Control Activity and Geographic Location

To test CONFOUND SBW and hopefully reduce rising SBW populations, three 150 hectare areas (see maps in Attachments) would be treated with one application of CONFOUND SBW at a rate of 50 g of active ingredient per hectare. This product is mixed with water and applied at an application volume of 3 litres per hectare. Guar gum, a thickening product used by the food, cosmetic and pharmaceutical industries (see SDS in Attachments), is added to the spray mix at a rate of 0.25% (weight by volume) to improve the rain fastness of spray deposits on the foliage. DayGlo fluorescent pigment is also added to the spray mix at a rate of ~ 0.3% weight by volume to confirm the accuracy and quality of the spray deposit within the target area. DayGlo pigment has been used in spray research since the early 1980's (see SDS in Attachments). Spray droplets containing DayGlo pigments are almost invisible to the naked eye in visible light but are easily detectable in a dark environment with ultra-violet light. In addition to the three treatment block three control block will be monitored for comparative analysis (See maps in Attachments)

Treatment Procedures

Under a Pesticide License from the Department of Environment, Climate Change, and Municipalities the Department of Fisheries, Forestry and Agriculture; Forestry and Wildlife Branch; Forest Engineering & Industry Division; Forest Insect & Disease Control Section has routinely overseen aerial protection programs against major forest pests in the Province. It maintains the equipment and infrastructure needed to conduct aerial treatments of forest areas. It has followed all Provincial and Federal legislation and regulation in conducting these programs. Prior to conducting any treatments, it has consulted with the various Provincial Departments and Stakeholders to address any concerns. It has worked with certified aerial applicators and conducted all treatments under the conditions specified within the Pesticide License.

Physical Features / Construction / Operation

No capital equipment will be purchased for this project and no structures will be constructed. Equipment already owned by Agrifor Biotechnical Services Ltd. will be brought from New Brunswick for the purpose of preparing the pheromone spray mix and assessing the field efficacy of the product. The pheromone product will be stored in the 20 litre pails in which it will be received and prepared immediately prior to use at the site designated for this purpose and in accordance with local requirements. Only individuals with a valid pesticide applicator's certificate will be permitted to mix, load or apply the pheromone product. Empty pheromone containers will be thoroughly cleaned and any rinsate which cannot be applied to the designated treatment area together with any other waste will be disposed of according to local requirements.

Helico Air Services will provide a Robinson R44 helicopter, DGPS Navigation System, Apollo DTM II spray system equipped with AU 5000 micronair atomizers. The aircraft will arrive on site calibrated as required and verified with attest of flow rate and swath width confirmation.

Occupations

The various occupations working on this project are divisible by function: Helico Air Services Limited will be conducting the aerial application; Chris Riley will represent Agrifor Biotechnical Services and will be providing the technical direction of the project; and the Department of Fisheries, Forestry and Agriculture will be provide ground, field, and laboratory support

Agrifor Biotechnical Services Ltd will support the project with Christopher Riley, a career specialist in Pesticide Application and Pesticide Risk reduction and one or two research assistants. The research assistants will be brought from New Brunswick or hired locally for the purpose of assessing the immediate post-application effects of the pheromone applications in July/August and then the effects of the treatment on second instar spruce budworm populations in October/November.

Research assistants will be employed to work in Newfoundland on a part-time basis for a total period of approximately six to nine weeks. Potential candidates, male or female, will be selected based on previous experience and their ability to meet the requirements of the position.

Helico Air Services will provide one pilot and licensed and one certified ground support crew. The 2 employees from Helico Air Services of are male.

Fourteen employees from the Department of Fisheries, Forestry and Agriculture will work on this project for a duration of two to three weeks intermittently. Six of 14 employees are female (43%) and 8 of the employees are male (57%).

Project Related Documents
See Attachments.

Worker Safety
The Department of Fisheries, Forestry and Agriculture has well established risk management and safety guidelines for contractors and workers involved in aerial control operations. Under the Pesticide Operators License all workers must be provided with appropriate PPE in accordance with the pesticide product label and material safety data sheet. These will be followed for this undertaking.

PUBLIC HEALTH CONSIDERATIONS
All label directions to be followed with respect to handling, treatment, and disposal. All conditions specified within the Pesticide License with respect to a Public Notice one to two weeks prior to treatment; a website and toll free number to provide daily updates; and signage along roadways close to treatment areas prior to treatment to be adhered to.

ENVIRONMENTAL SAFETY
All label direction to be followed. All conditions specified within the Pesticide License to protect the Environment will be followed. Forest Service Branch environmental management system standard operating practices (see SOP's in Attachment) for aerial control operations will also be followed for this undertaking.

PUBLIC NOTIFICATION
Public notification as indicated under the Public Health Consideration Section.

POTENTIAL CONFLICTS
No potential conflicts were identified for the areas identified for treatment.

ALTERNATE OPTIONS FOR SPRUCE BUDWORM CONTROL

No other options exist with respect to testing this particular control product.

APPROVAL OF THE UNDERTAKING
Part 5 of the Provincial Forestry Act, Section 88, indicates the minister may undertake all reasonable measures to provide for effective protection of the forests whether on Crown lands, public land or privately owned land. .

SCHEDULE
Biological timing of treatment anticipated to occur around the third week to the end of July

moth flight as determined using pheromone traps.

FUNDING

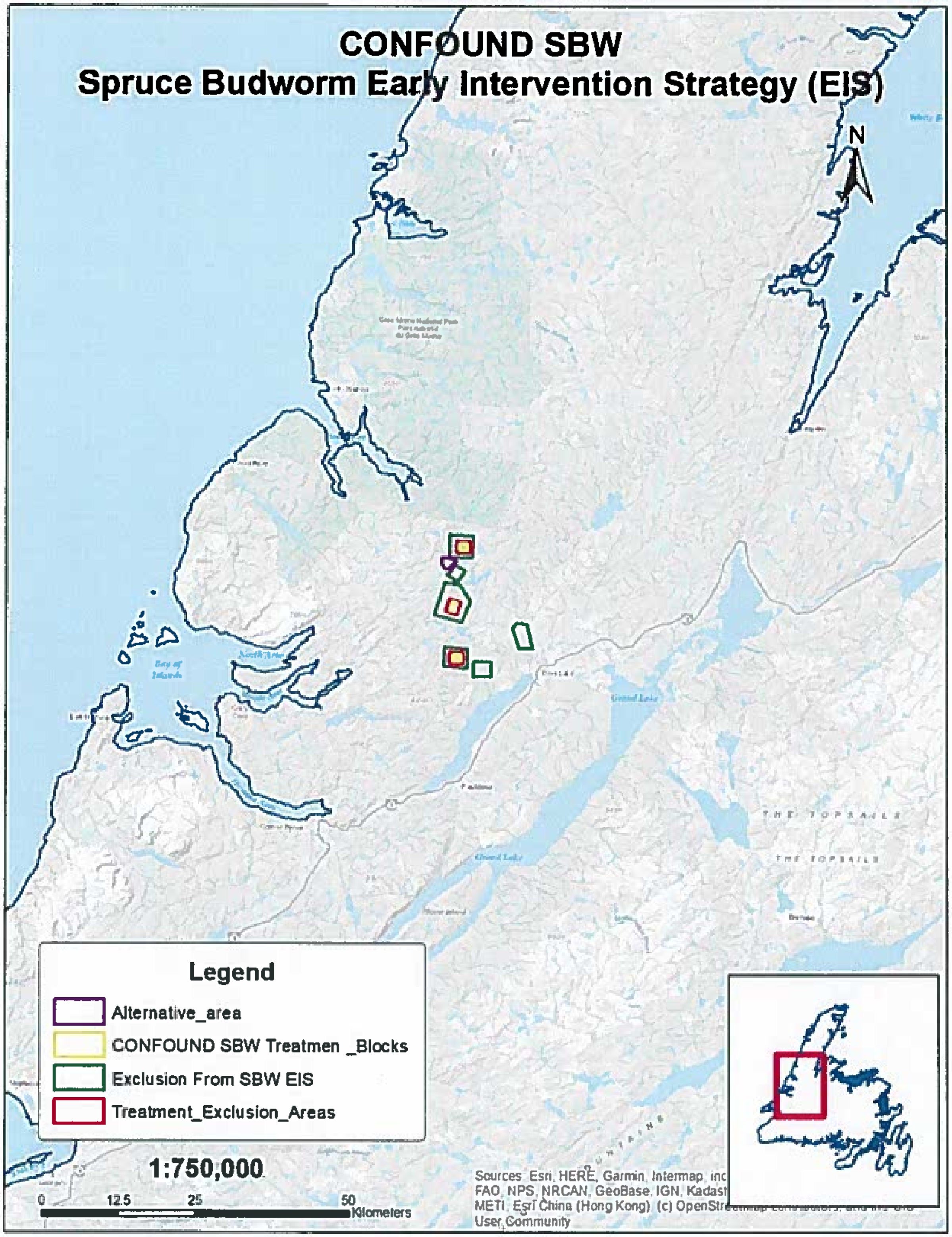
This project is funded through the Atlantic Canada Opportunities Agency (ACOA) under the Atlantic Innovation Fund (AIF). Acadia University is the lead agency on this research project. This project has leveraged additional research dollars from Spray Efficacy Research Group International (SERG-I) and in-kind assistance from the Department of Fisheries, Forestry and Agriculture.

May 13, 2021
Date

Original signed by
Colin Carroll
Director, Department of Fisheries, Forestry and Agriculture

ATTACHMENTS

Maps of proposed treatment and control blocks, CONFOUND SBW label, SDS, additional literature and EMS SOP's


CONFOUND SBW
Spruce Budworm Early Intervention Strategy (EIS)
N
Bay of Islands
Grand Lake
THE TOPSAILS
Legend
Alternative_area
CONFOUND SBW Treatmen _Blocks
Exclusion From SBW EIS
Treatment_Exclusion_Areas
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Sources: Esri, HERE, Garmin, Intermap, inc
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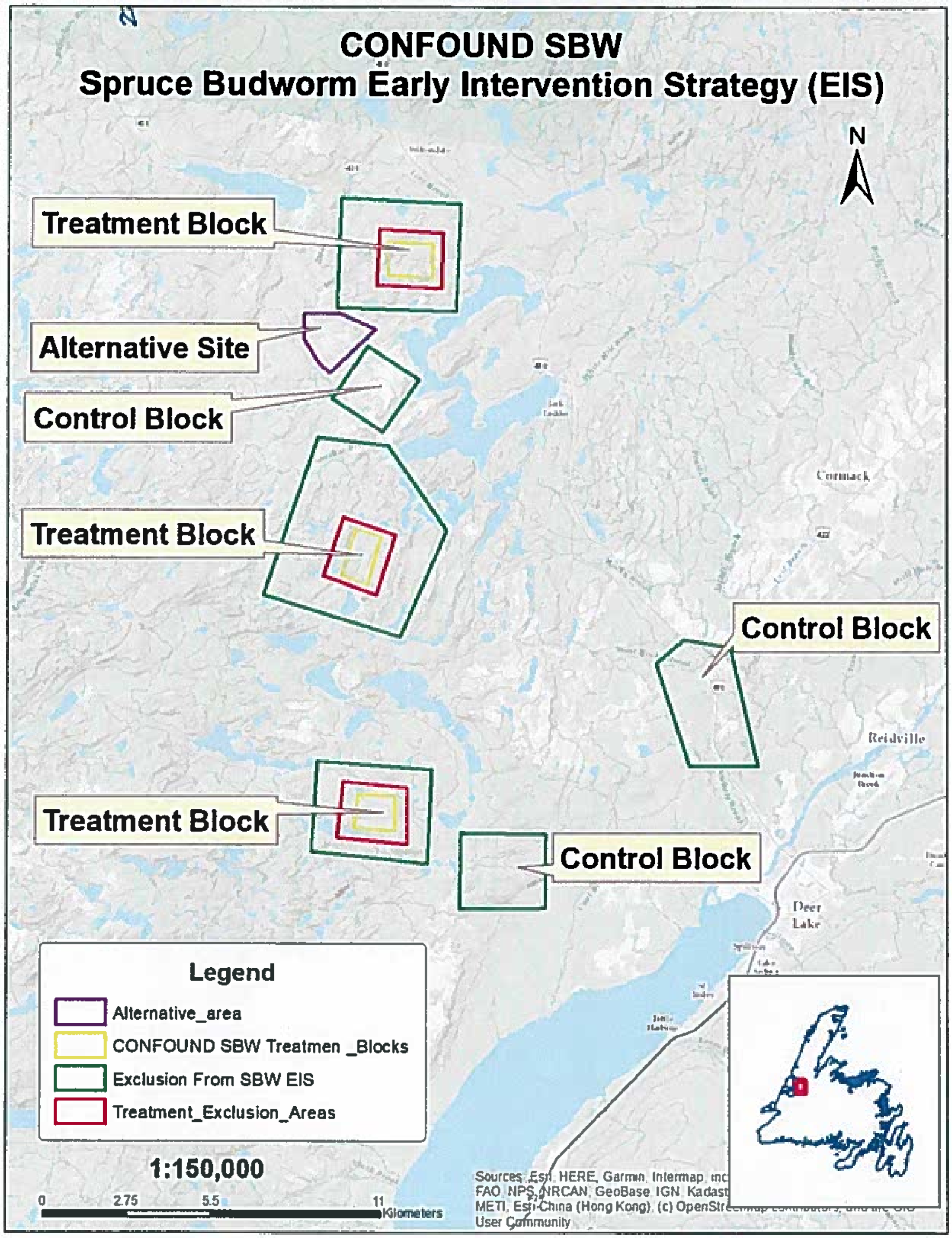
CONFOUND SBW
Spruce Budworm Early Intervention Strategy (EIS)
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Treatment Block
Alternative Site
Control Block
Treatment Block
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Cormack
Reidville
Deer Lake
Legend
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CONFOUND SBW Treatmen _Blocks
Exclusion From SBW EIS
Treatment_Exclusion_Areas
1:150,000
0 2.75 5.5 11 Kilometers

2018-0749
2018-02-23

CONFOUND$_{SBW}$

With Spruce Budworm Pheromone
For Mating Disruption

Mircoencapsulated pheromone for mating disruption of the spruce budworm, *Choristoneura fumiferana* (Clemens)

COMMERCIAL
INSECTICIDE
MICROENCAPSULATED SUSPENSION

READ THE LABEL BEFORE USING
KEEP OUT OF REACH OF CHILDERN

GUARANTEE: 95E:5Z (E,Z)-11-Tetradecenal, 11%

REGISTRATION NUMBER: 32730 PEST CONTROL PRODUCTS ACT

Net Contents: 203L
1000L

CAUTION- SKIN AND EYE IRRITANT

Manufactured by: Vantage
707 Harco Drive
Englewood, Ohio 45315 USA

Distributed By: Sylvar Technologies Inc.
1350 Regent Street
Fredericton, NB E3C 2G6 Canada
Tel: 1-888-870-6444

Batch Number:
Date of Manufacture:

CONFOUND$_{SBW}$

With Spruce Budworm Pheromone
For Mating Disruption

RESTRISTED USES
FOREST AND WOODLANDS
NOTICE TO USER: This pest control product is to be used only in accordance with the directions on the label. It is an offence under the Pest Control Products Act to use this product in a way that is inconsistent with the directions on the label. The user assumes the risk to persons or property that arises from any such use of this product.
NATURE OF RESTICTION: This product is to be used only in the manner authorized; consult local provincial regulatory authorities about use permits that may be required.
RESTRICTED USE: For use against spruce budworm (*Choristoneura fumiferana* (Clemens)) in forests and woodlands. Apply at the rate recommended.

DIRECTIONS FOR USE

CONFOUND$_{SBW}$ is intended to diminish spruce budworm (*Choristoneura fumiferana*) mating by interfering with pheromone-mediated communication between adult moths. Disrupting communication between adult moths may result in decreased egg laying and therefore reduced larval populations, and decreased feeding damage in forests and woodlands. Apply the product as a single application immediately prior to, or at the onset of, moth emergence. The recommended application rate of CONFOUND$_{SBW}$ is 50-80 g ai/ha per application. The product should be diluted with water and applied in a total volume of 2 to 5 L per hectare. The use of a proven adjuvant to improve the rainfastness of the product is recommended.

The product is recommended for aerial application. Effective application and distribution of this product throughout the forest canopy cannot be achieved with a field sprayer.

AERIAL APPLICATION INSTRUCTIONS

Apply only by fixed-wing or rotary aircraft that has been functionally and operationally calibrated for the atmospheric conditions of the area and the application rates and the conditions of this label. Label rates, conditions and precautions are product specific. Apply only at the recommended rate on this label. Ensure uniform application by using appropriate marking devices and/or electronic tracking equipment.

ENVIRONMENTAL PRECAUTIONS

As this product is not registered for the control of pests in aquatic systems, DO NOT use to control aquatic pests.

DO NOT contaminate irrigation or drinking water supplies or aquatic habitats by cleaning of equipment or disposal of wastes.

PRECAUTIONS

KEEP OUT OF THE REACH OF CHILDREN

DO NOT inhale or breathe in any dust generated prior to, during or after application. Causes eye irritation. DO NOT get into eyes.
During mixing, loading, clean-up or repair of equipment, personnel should wear an appropriate respirator, chemical resistant gloves, coveralls, goggles or face shield, long-sleeve shirt, long pants, shoes and socks.
Apply only when meteorological conditions at the treatment site allow for complete and even coverage.
Apply only when meteorological conditions are in compliance with the requirements of local and/or provincial authorities.

FIRST AID
If Swallowed: Call a poison control centre or doctor immediately for treatment advice. Have person sip a glass of water if able to swallow. Do not induce vomiting unless told to do so by a poison control centre or doctor. Do not give anything by mouth to an unconscious person.
If on Skin or Clothing: Take off contaminated clothing. Rinse skin immediately with plenty of water for 15-20 minutes. Call a poison control centre or doctor for treatment advice
If Inhaled: Move person to fresh air. If person is not breathing, call 911 or an ambulance, then give artificial respiration, preferably mouth-to-mouth, if possible. Call a poison control centre or doctor for treatment advice.
If in Eyes: Hold eye open and rinse slowly and gently with water for 15-20 minutes. Remove contact lenses, if present, after the first 5 minutes, then continue rinsing eye. Call a poison control centre or doctor for treatment advice.
General: Seek medical attention immediately if irritation or signs of toxicity occur and persist or are severe. Take the container, label or product name and Pest Control Product Registration Number with you when seeking medical attention.

TOXICOLOGICAL INFORMATION: Treat symptomatically

Storage: Store in a cool dry place. Do not store at sub-zero temperatures.

DISPOSAL:
1. Triple or pressure-rinse the empty container. Add the rinsings to the spray mixture in the tank.
2. Follow provincial instruction for any required additional cleaning of the container prior to its disposal.
3. Make the empty container unsuitable for further use.
4. Dispose of the container in accordance with provincial requirements
5. For information on disposal of unused, unwanted product, contact the manufacturer or the provincial regulatory agency. Contact the manufacturer and the provincial regulatory agency in case of a spill, and for clean-up of spills.

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REVIEW ARTICLE

Sex Pheromones and Their Impact on Pest Management

Peter Witzgall · Philipp Kirsch · Alan Cork

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Abstract The idea of using species-specific behavior-modifying chemicals for the management of noxious insects in agriculture, horticulture, forestry, stored products, and for insect vectors of diseases has been a driving ambition through five decades of pheromone research. Hundreds of pheromones and other semiochemicals have been discovered that are used to monitor the presence and abundance of insects and to protect plants and animals against insects. The estimated annual production of lures for monitoring and mass trapping is on the order of tens of millions, covering at least 10 million hectares. Insect populations are controlled by air permeation and attract-and-kill techniques on at least 1 million hectares. Here, we review the most important and widespread practical applications. Pheromones are increasingly efficient at low population densities, they do not adversely affect natural enemies, and they can, therefore, bring about a long-term reduction in insect populations that cannot be accomplished with conventional insecticides. A changing climate with higher growing season temperatures and altered rainfall patterns makes control of native and invasive insects an increasingly urgent challenge. Intensified insecticide use will not provide a solution, but pheromones and other semiochemicals instead can be implemented for sustainable area-wide management and will thus improve food security for a growing population. Given the scale of the challenges we face to mitigate the impacts of climate change, the time is right to intensify goal-oriented interdisciplinary research on semiochemicals, involving chemists, entomologists, and plant protection experts, in order to provide the urgently needed, and cost-effective technical solutions for sustainable insect management worldwide.

Keywords Sex pheromone · Attraction · Monitoring · Attracticide · Mating disruption · Insect control · Integrated pest management · Food security

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50 Years of Pheromone Research

Fifty years of curiosity driven pheromone research have yielded a profound understanding of sexual communication in insects. The discovery that minute amounts of species-specific chemical signals, encoded by discrete receptors on the antenna, instantaneously elicit a conspicuous upwind flight orientation behavior has been a source of inspiration for fundamental research on the insect olfactory system; research ranges from biosynthetic production of sex pheromones to peripheral perception by odorant receptor neurons, central processing of the olfactory input, and the resulting behavior (Jacquin-Joly and Merlin 2004; Jefferis et al. 2007; Xue et al. 2007; Cardé and Willis 2008; De Bruyne and Baker 2008).

The progress that has been made from the identification of the first sex pheromone in the silk moth by Butenandt and coworkers in 1959 to the identification of olfactory receptors in *Drosophila* (Clyne et al. 1999; Vosshall et al. 1999) and in the silk moth (Krieger et al. 2005) is spectacular. Pheromone communication, including the generation of behavioral responses, is now being dissected at a molecular level (Benton et al. 2007; Dickson 2008). Our imagination is not sufficient to envision knowledge in insect olfaction and chemical ecology another 50 years from now, provided that researchers have the mandate and the resources to carry on this work.

Fundamental research derives, in part, its motivation and justification from the prospect of applying the acquired knowledge. A characteristic of insect chemical ecology is that the know-how can be transferred and used for the control of insects that are noxious to plants or animals. The interconnection between fundamental and applied research, the academic sector, chemical industries, agriculture, horticulture, and forestry, has been a driving force in fundamental and applied pheromone research. Many who began pheromone research in the sixties were influenced by the concept of integrated pest management (Stern et al. 1959) and Rachel Carson's (1962) plea for biorational pesticides. The use of synthetic pheromones for environmentally safe insect control was postulated soon after the discovery of silk moth pheromone (Butenandt et al. 1959; Wright 1964), well before pheromones of economically important insect pests were known.

Fifty years after bombykol, the database of insect pheromones and related attractants contains hundreds of chemicals (Arn et al. 1992; El-Sayed 2008). Pheromones are used as monitoring tools worldwide, and pheromone-based control applications cover large areas (Ridgway et al. 1990b; Howse et al. 1998; Baker and Heath 2004). Behavior-modifying chemicals are elegant tools for insect control, and the prospect of a wide range of future applications in agricultural and medical entomology continues to fuel research in insect olfactory physiology and chemical ecology (Van der Goes van Naters and Carlson 2006). The idea of replacing hazardous insecticides with environmentally benign and species-specific odorants is still a current research challenge, but the emphasis is shifting. The motivating force for green, sustainable insect control is no longer merely the health of the rural work force, the safety of agriculture and horticultural products, nor even the attempt to promote organic farming. The matter is more urgent than it was 50 years ago, and our concerns are the necessity of establishing sustainable insect control methods in times of increasing food insecurity.

Sustainable Insect Control and Food Security

Population growth, creating an increased demand for food, intensifies the pressure on our natural resources, and the adverse effects of climate change on agroecosystems further accentuates the magnitude of this challenge (Ehrlich et al. 1993). Foremost among the Millennium Development Goals endorsed by the United Nations is to eradicate extreme hunger and poverty and, more precisely, to halve between 1990 and 2015 the proportion of people who suffer from hunger. (www.un.org/millenniumgoals). Obviously, our endeavor to secure food for a growing population is closely related to another millennium goal, i.e., to reduce the loss of environmental resources and biodiversity. As we approach the deadline for the fulfillment of these goals, advances have begun to slow or even to reverse.

Environmental security and food security are closely interrelated and mutually dependent. Intensified pressure on ecosystems leads to depletion of resources that are vital for agriculture, including natural enemies of insect pests, pollinators, and carbon sequestration (Ehrlich et al. 1993; Thrupp 2000; van Mantgem et al. 2009). Moreover, future crops will grow under a different climate. The predicted associated effects of higher growing season temperatures and altered patterns of precipitation will have substantial impact on all forms of land use, from agriculture land and forests to aquatic environments. (Battisti and Naylor 2009; Schlenker and Roberts 2009).

Climate changes also will influence plant health and vigor, directly and indirectly through a modified reproductive performance of their associated herbivores. Climatic change will alter outbreak patterns and geographical ranges of insects, including those that vector diseases. The consequences are difficult to predict, especially in view of the complex interactions between crops, herbivores, and pathogens, but climate-related changes most likely will combine to reduce yields (Hunter 2001; Gregory et al. 2009). Forest insects have provided the first conspicuous examples of how insect outbreaks are intensified by global warming. Higher temperatures and drought are blamed for violent bark beetle attacks across Northern America that impact forest structure and in consequence carbon sequestration (Kurz et al. 2008; Van Mantgem et al. 2009).

Up to one third of worldwide food production is destroyed by insects, not including the damage done in storage. During decades of insecticide use, a permanent decrease in the abundance of targeted insect populations never has been achieved. Many of our top agricultural pests instead have been created by the use of pesticides that often have a stronger effect on natural antagonists than on the target species, and also because of widespread insecticide resistance (Pimentel et al. 1992; Elzen and Hardee 2003; Oerke 2006). This is particularly relevant in developing countries, where agricultural production must be increased to feed the population (Thrupp 2000; Pretty et al. 2003; Nwilene et al. 2008).

While crop protection against insects has long relied on insecticides, it is clear that they alone cannot provide a solution, not even by further intensification of their application. Shortcomings are particularly obvious in regions with warm climates and long growing seasons. Recognition of pesticide limitations has, for example, led to the development of pheromone-based methods for control of the rice stem borer *Scirpophaga incertulas* in Bangladesh. Rice covers 70% of the land available for agriculture. Yield has increased by over 40% from 1996 to 2001, yet it does not match consumption. The annual insecticide application has increased from 7,000 t in 1997 to more than 16,000 t in the year 2000, some 90% of which is used in rice production. Even some agrochemical industries now have reached the view that a further increase is not feasible, and thus they support the development of mating disruption and mass trapping of rice stem borer in order to maintain a sustainable level of pesticide use (Cork et al. 2005b).

Chemical ecology produces the knowledge of non-toxic and species-specific pheromones and other semiochemicals that do not harm beneficial species and thus, the basis for efficient and sustainable insect management strategies. The paradox is that currently available know-how is not sufficiently exploited, and we may not be investing enough in research and development to provide breakthroughs quickly enough, especially in food-deficient countries in the developing world. Development aid to agriculture declined by almost 60% between 1980 and 2005, even though the total development aid bill increased over the same period (Fig. 1). In this review, one of our goals was to demonstrate that it is timely and meaningful to invest further in research on behavior-modifying chemicals for sustainable insect management.

Successes and Constraints of Pheromone-Based Methods

"There are many other reasons for using pheromones; one is that they are elegant" (Arn 1990). Three main elements account for the fascination of insect sex pheromones and their feasibility for insect management: 1) they are species-specific, 2) they are active in very small amounts, and 3) the vast majority are not known to be toxic to animals.

Pheromones are by definition species-specific, since the discrimination of conspecific and heterospecific pheromone signals is a key element in the evolution of specific mate recognition systems in many insects. Even synthetic, incomplete pheromone blends usually affect only the target, with the possible exception of taxonomically closely related species (Cardé and Haynes 2004).

Insects use extremely small amounts of pheromone for communication. For example, calling females of codling moth *Cydia pomonella* release pheromone at a rate of several ng/h. [In comparison, apple trees in orchards release one main volatile compound, (*E*,*E*)-α-farnesene, at an estimated rate of several g/ha/h (Witzgall et al. 2008)]. Pheromone trap lures used for detection and monitoring release typically ten to 100 times more than a calling female, and mating disruption dispensers used in orchards release up to 10,000 times more codlemone, which amounts to release rates of 10–100 mg/ha/h. The seasonal application rate of codlemone for mating disruption of codling moth in orchards is up to 100 g/ha. Worldwide annual production of codlemone is ca. 25.000 kg (Fig. 2), for codling moth control on ca. 210.00 ha.

Regulatory agencies in several countries consider it safe to use lepidopteran pheromones. This was corroborated by a recent evaluation by the California Environmental Protection Agency on the occasion of an area-wide eradication campaign against light brown apple moth (Ting 2009). Many pheromones have been registered for pest control, and there is no evidence of adverse effects on public health, non-target organisms, or the environment. Pheromones are applied in slow release formulations, thus resulting in low exposure; residues of lepidopteran pheromones in pheromone-treated food crops have not been detected (Tinsworth 1990).

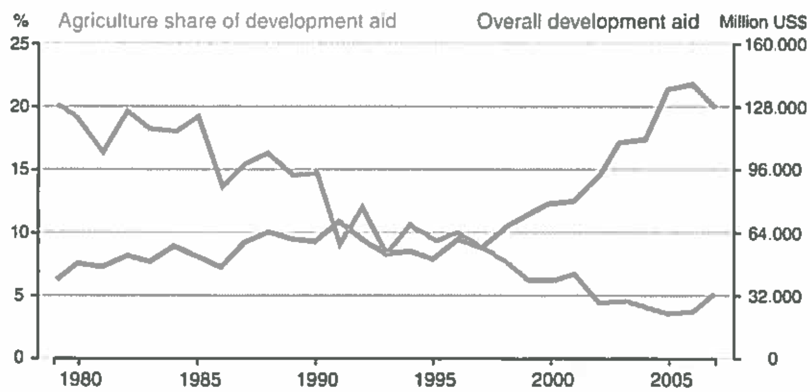

Fig. 1 Overall development aid (*right* scale, million US$), and the share dedicated to agriculture (*left* scale), 1979 to 2007 (Food and Agriculture Organization, FAO; World Summit on Food Security, Rome, November 2009)

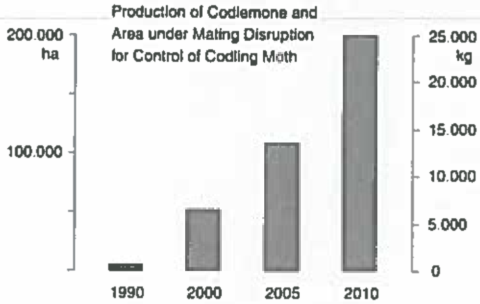

Fig. 2 Production of codling moth *Cydia pomonella* pheromone and area under mating disruption against codling moth worldwide (above; data courtesy of Shin-Etsu Chemical Co., Tokyo)

Insecticides vs. Pheromones

Insecticides do not achieve a long-term pest population decrease. In contrast, an observation shared by many working with pheromone-based control is that continuous long-term use *does* decrease population levels of target species (Fig. 3; Witzgall et al. 1999; Varner et al. 2001; Ioriatti et al. 2008; Weddle et al. 2009). This is attributable to a recovering fauna of beneficials, and to an increasing efficacy of pheromones at low population densities, when communication distance between sexes is increasing.

Insecticide overuse also induces outbreaks of secondary pests. Predatory and phytophagous mites provide the classic example of how the natural regulation of herbivores by their antagonists is disturbed by broad-spectrum pesticides (Agnello et al. 2003). Replacing insecticide with pheromone treatments in vineyards and orchards has rendered treatments against phytophagous mites superfluous, which compensates for the cost of the pheromone treatment (Louis et al. 1997; Waldner 1997; Jones et al. 2009). This emphasizes the contributing vital role of natural enemies for population control, and it corroborates that pheromone-based methods produce better results in the long run, due to recovery of the beneficial fauna.

Insects with hidden, protected lifestyles, including those with underground or woodboring larval habits, cannot easily be controlled with cover sprays of insecticides. Here, control with pheromones is advantageous, since it aims at the mobile adult life stage, and functions to prevent oviposition altogether. Examples of successful pheromone applications are provided in the sections below, and many of these concern insects that inflict severe damage and that are difficult or expensive to control with insecticides.

Slow Development of Pheromone-Based Pest Management

Despite their advantages, progress with practical implementation and commercial exploitation of pheromones has been slow. In Europe, pheromones have been used widely for almost two decades; against the grapevine moths *Lobesia botrana* and *Eupoecilia ambiguella* in Germany, Switzerland, and Northern Italy (Fig. 3; Arn and Louis 1996; Varner et al. 2001; Ioriatti et al. 2008) and against codling moth *Cydia pomonella* in Switzerland and Northern Italy (Mani et al. 1996; Waldner 1997). Although similar climatic, faunistic, and economic conditions exist in other

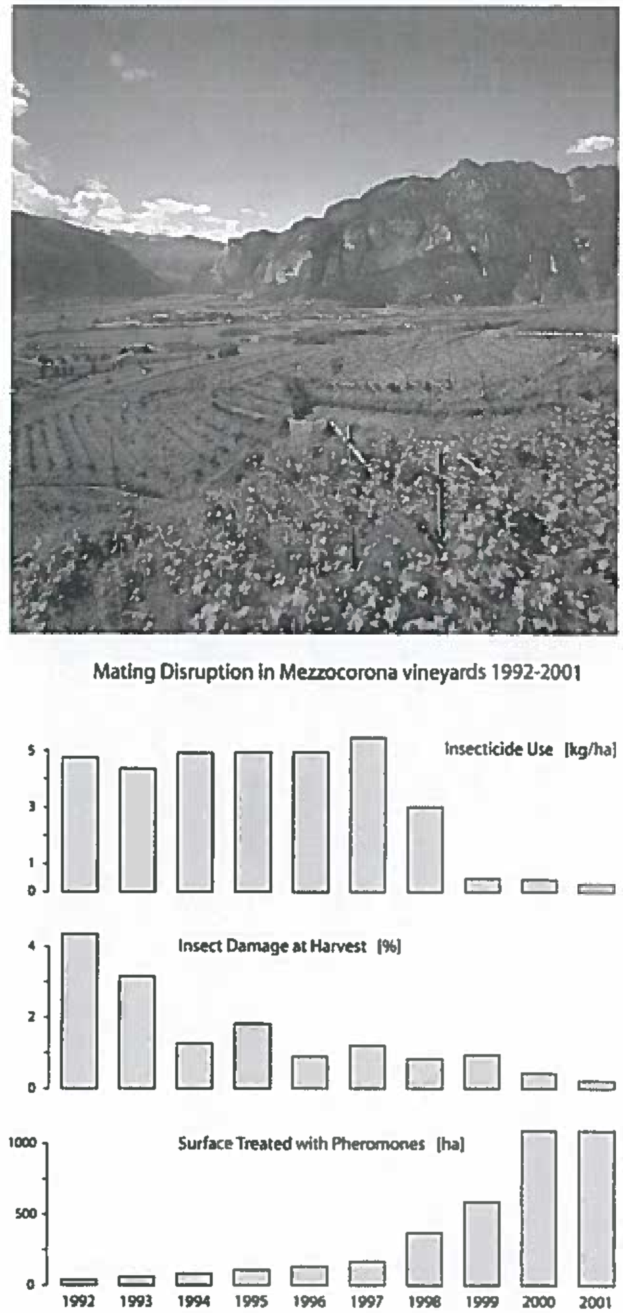

Fig. 3 Mating disruption in the Mezzocorona vineyards in Trento, Italy (Mauro Varner and Claudio Ioriatti, pers. comm.; photo by Mauro Varner)

European wine- and fruit-growing areas, pheromones have not been used much until very recently.

This suggests that motivation and determination among those involved in development and operation of pheromonal pest control methods is a key factor. A certain inertia in the pest control sector to adopt new technologies may be sustained by the lack of interest among research scientists in promoting and transferring existing knowledge. Ehrlich et al. (1993) convincingly argued that the historical separation of agriculture and pure biology at most universities has prevented the implementation of ecological principles in agriculture. To some extent, this may still be true today.

Another key to a more widespread use of pheromones is that the technologies currently in use must become more reliable. Continued goal-oriented research will lead to both more reliable and hence more widespread applications, but funding for applied research at academic institutions and extension services is being cut in many countries (Jones et al. 2009). Field implementation should become a focus of future pheromone research.

Few conventional chemical industries have invested in pheromones, and this lack of engagement has led to the belief that pheromone technology is not viable economically. More smaller companies that specialize in a particular product type, and have the flexibility and low overheads to make their investments in semiochemical products financially viable, are needed.

Practical pheromone applications depend on availability of efficient dispenser materials and on the economic synthesis of pheromone chemicals. The price of synthetic codlemone in the beginning of the nineties, for example, was far too elevated for commercial area-wide applications, but development of large-scale synthesis (Yamamoto and Ogawa 1989) made it possible to exploit it commercially. The annual production of codlemone, the main pheromone compound of codling moth, is on the order of 25 t (Fig. 2), and the price of codlemone is now well below 1,000 US$/kg.

Motives for Area-Wide Pheromone Use

The pheromone application concept goes beyond the conventional control paradigm of protecting plants against larval infestation with sprays of toxic compounds. Conditions for pheromone use are more favorable in area-wide programs, where the effect of immigrating, mated insect females becomes negligible. Successful use is frequently based on a joint effort that involves research scientists, extension entomologists, growers' associations, and also pheromone industries. Area-wide projects facilitate and provide support for this organizational effort (Ioriatti et al. 2008; Jones et al. 2009; Weddle et al. 2009).

The economic benefits of implementing sustainable techniques become evident at the landscape level. A close inspection of pheromone technologies that have been in place over several years shows that the price of pheromones vs. insecticides should not be confounded with economy of use. Farmers' efforts and successes in establishing sustainable production methods contribute to rural development (Ioriatti et al. 2008).

Safe insect control techniques not only improve product quality, but also contribute to the image of a region. Insecticide drift and run-off pollutes air and groundwater, and reduction of insecticide sprays alleviates growing conflicts between rural and urban areas. Orchards and vineyards, where pheromone-mediated mating disruption is widely used, are a part of cultural landscapes that produces, in addition to horticultural products, revenues by attracting tourists, enterprises, investors, and people who wish to inhabit this land.

Detection and Monitoring

The most widespread and successful applications of sex pheromones concern their use in detection and population monitoring. Captures in traps baited with synthetic pheromone lures accurately show whether a specific insect is present, and when its seasonal flight period starts. A simple and widespread strategy is to time insecticide sprays accordingly.

Population monitoring relates trap captures to the abundance of, or to the damage caused by an insect species. The magnitude of trap captures is used to determine thresholds, either for the timing of control procedures, or for making the decision whether or not remedial action is to be taken. One of the first widely used monitoring systems that include an action threshold based on trap captures was established for pea moth *Cydia nigricana* (Wall et al. 1987). Pheromone traps are sensitive enough to detect low-density populations, and are, therefore, effective for tracking invasive species in the establishment phase (El-Sayed et al. 2006; Liebhold and Tobin 2008).

Since pheromones lures are inexpensive and usually reliable, they facilitate the Integrated Pest Management (IPM) concept, which relies on frequent scouting of target species for planning of control measures and evaluating their efficacy. This is particularly so when more specific tools such as semiochemicals, microbials, or beneficials are used, rather than broad-spectrum insecticides.

Invariably, pheromone traps capture adults, and often only males, as is the case with lepidopteran pheromones. When trapping information is to be used in a predictive manner, such as in the damage done by the next generation of larvae, a good understanding of the biology of the pest and the effect of weather and crop stage on development is needed. For pheromone-based monitoring it is further essential that a number of parameters, including the attractant, dispenser, trap design, and trap location are standardized and kept constant. The attractant and dispenser material must be under strict quality control, since release rates and chemical impurities, even in trace amounts, will strongly affect the attractiveness of a lure (Arn et al. 1997). Lure constancy, not overall attractiveness, is decisive.

One future goal is data capture. Insect monitoring can be facilitated by supplying farmers with additional information that includes current and historical seasonal records of trap catch, infestation rates, climate data, and possibly even the geographical distribution of the crop and target insect. This can be aided by the use of geographical information systems (GIS), for example, in area-wide control programs in forests (see below; Tobin et al. 2004, 2007).

Practical Use of Pheromone-Baited Traps

Hundreds of pheromone compounds have been identified, most of them in Lepidoptera, but also in other insect orders, particularly beetles and flies (Arn et al. 1992; El-Sayed 2008). Table 1 shows widely used pheromone lures. In several species, such as the tomato leafminer *Tuta absoluta* and in stored product insects, lures are used for both monitoring and mass trapping (see below). Lures are distributed by many companies worldwide, and there are no reliable data on the total number used, especially in emerging markets in Asia and South America. We estimate that at least 20 million pheromone lures are produced for monitoring or mass trapping every year. This includes all pest control sectors, horticulture, agriculture, stored products, forests, and also private use in households and gardens.

Gall midges (Diptera: Cecidomyiidae) are, because of their small size, difficult to see, and pheromones are cost-effective tools for tracking these tiny flies. Gall midge pheromone identifications require state-of the-art analytical techniques, since they are produced in pico- to femtogram amounts. The chemical structures are carbon chains with one or two ester functionalities, and have been identified from several species including Hessian fly *Mayetolia destructor* (Andersson et al. 2009), swede midge *Contarinia nasturtii* (Hillbur et al. 2005), and raspberry cane midge *Resseliella theobaldi* (Hall et al. 2009). Swede midge traps have been deployed along the US-Canadian border to determine the geographical range of this invasive insect. A combination of a predictive model with pheromone traps accurately assesses and times control strategies (Hallett et al. 2009).

The tomato leafminer, *Tuta absoluta*, is an example of how the absence of an efficient conventional chemical control or other biological method encourages the use of an immature pheromone technology for insect control, merely because other methods are not available. *T. absoluta* is a multivoltine species that mines leaves and fruits of solanaceous plants. Effective chemical control is difficult to achieve (Pereyra and Sanchez 2006). Originally of neotropical distribution, *T. absoluta* recently has been introduced to Southern Europe and Northern Africa. This has fuelled the demand for monitoring lures, which are now employed in mass trapping campaigns in greenhouses. The main sex pheromone component is a triene, (E,Z,Z)-3,8,11-tetradecatrien-1-yl acetate (Svatos et al. 1996), but the lack of an economic synthesis currently precludes mating disruption tests.

Pheromone identifications in beetles are less advanced than in moths. Aggregation pheromones currently are used for mass trapping of weevils and scarabs (see below), and sex pheromones of several other families are under investigation. Larvae of click beetles are hard to control with pesticides due to their underground life habit. One main compound of click beetle pheromones is geranyl octanoate, and specific blends have been identified in several species. Pheromones have been used to survey species distributions and to monitor in the field, for example, *Agriotes* sp. in Europe and North America (Vernon and Toth 2007; Toth et al. 2008).

A number of pheromones have been elucidated in cerambycid beetles over the past decade. Even weak attraction to generic blends may be sufficient for monitoring distribution and phenology. However, some pheromones even attract females, and many of these species have long life cycles with short adult stages, which should favor the use of pheromones for control (Maier 2008; Ray et al. 2009; Rodstein et al. 2009). The coffee white stem borer *Xylotrechus quadripes* is a serious pest of coffee in South Asia. Male beetles have been shown to attract females, and (S)-2-hydroxy-3-decanone has been identified as the main attractive compound. Pheromone traps have been rapidly adopted for mass trapping (Table 1; Hall et al. 2006) reflecting exceptional grower interest in the absence of acceptable alternative control methods.

Mass Trapping and Annihilation

Control of insect populations with pheromones is achieved by two principle techniques, mating disruption and mass annihilation. Mating disruption (see below), causes disorientation and communication disruption between the sexes, and thus delays, reduces, or prevents fertilization of females. Mass annihilation, by mass trapping or attract-and-kill, relies on attraction of one or both sexes to a lure, in combination with a large-capacity trap or an insecticide-

Table 1 Use of sex pheromone lures for detection (D) and population monitoring (M), and for mass annihilation tactics, by mass trapping (MT) and attract-and-kill (AK)

Species	Purpose	Region	Lures/year
Horticulture			
Coleoptera			
Red palm weevil *Rynchophorus ferrugineus*	MT	Asia	1.175.000
American palm weevil *Rhynchophorus palmarum*	MT	Central and South America	25.000
Palm fruit stalk borer *Oryctes elegans*	MT	Asia	125.000
Banana weevil *Cosmopolites sordidus*	MT	Worldwide	120.000
Coffee white stem borer *Xylotrechus quadripes*	MT	India	40.000
Diptera			
Olive fruit fly *Bactrocera oleae*	MT, AK	EU	–[a]
Lepidoptera			
Grapevine moth *Lobesia botrana*	M	EU, Mediterranean countries, Chile, USA	–
Codling moth *Cydia pomonella*	M, AK	Worldwide	–
Oriental fruit moth *Grapholita molesta*	M, AK	Worldwide	–
Tomato leafminer *Tuta absoluta*	M, MT	South America, EU, North Africa	2.000.000
Brinjal fruit and shoot borer *Leucinodes orbonalis*	MT	India, Bangladesh	400.000
Fall armyworm *Spodoptera frugiperda*	MT	Central America	50.000
Agriculture			
Coleoptera			
Cotton boll weevil *Anthonomus grandis*	MT (AK)	North and South America	2.600.000
Click beetles *Agriotes spec.*	M	Europe	–
Lepidoptera			
Pink bollworm *Pectinophora gossypiella*	M, AK	North and South America, South Asia	–
Old World bollworm *Helicoverpa armigera*[b]	M, MT		830.000
Cotton leafworm *Spodoptera litura*[b]	M, MT		480.000
African armyworm *Spodoptera exempta*	D	East Africa	–
Spotted bollworm *Earias vittella*[b]	M, MT		280.000
Yellow rice stem borer *Scirpophaga incertulas*	M, MT	India	100.000
Southwestern Corn Borer *Diatraea grandiosella*	D	USA	–
Potato tuber moth *Phthorimaea operculella*	AK	South Africa	–
Forestry			
Coleoptera			
Spruce bark beetle *Ips typographus*	MT	Europe, China	800.000
Mountain pine beetle *Dendroctonus ponderosae*	MT	North America	–
Douglas-fir beetle *D. pseudotsugae*	MT	North America	–
Lepidoptera			
Gypsy moth *Lymantria dispar*	D	USA, EU	250.000
Spruce budworm, *Choristoneura fumiferana*	D	Canada, USA	–
Pine processionary moth, *Thaumetopoea pityocampa*	D, M	EU	–
Stored products			
Cigarette beetle *Lasioderma serricorne*	M, MT	Worldwide	2.500.000
Indian meal moth, *Plodia interpunctella*	M, MT	Worldwide	2.000.000
Households and gardens			
Japanese beetle *Popillia japonica*	MT	North America	–
Oriental beetle *Anomala orientalis*	MT	North America	–
House fly *Musca domestica*	MT	Worldwide	2.000.000
German cockroach, *Blattella germanica*, American cockroach, *Periplaneta americana*	MT	Worldwide	1.000.000

Examples of widely used lures. A distinction between monitoring and mass trapping is not always possible. The estimated number of lures used worldwide, based on turnover of leading companies in the US and Europe, exceeds 20 million lures

[a] No data available

[b] Data concern South Asia only

impregnated target. Unlike detection and monitoring, where only a small proportion of a population needs to be sampled, mass annihilation requires the use of the most attractive lure.

For attract-and-kill strategies, two different approaches are taken. Either, a semiochemical formulation, consisting of an attractant and inert carriers, is deployed as an additive tank-mix to insecticide products, or an attractant and insecticide are incorporated into a fully integrated matrix that can be applied as a stand-alone intervention. Each approach has specific merits. The additive approach has an advantage in that registration of semiochemicals is facilitated. When applying an integrated matrix product, blanket spray coverage of the crop is not necessary, so the amount of insecticide can be significantly reduced. However, specialized application technology is required.

With female-produced sex pheromones, only males are caught. Since male insects typically mate more than once, a high proportion of the male population must be removed to produce an effect. Male protandry, eclosion before females, will improve the effect of removing males. In addition, even a delay in mating, via a reduction in the number of available males, may also contribute to population control, as has been shown in mating disruption studies (Vickers 1997; Fraser and Trimble 2001; Jones et al. 2008; Stelinski and Gut 2009). These studies underscore the importance of integrating population biology and life history data into development of pheromone-based control applications. Population control is a dynamic and quantitative phenomenon, as illustrated by the importance of the Allee effects in the management of biological invasions (Liebhold and Tobin 2008).

Features of the biology and ecology of the target species that determine the efficacy of annihilation techniques include: the duration of the life cycle, the number of generations per season, the duration of the flight period, and the rate of population growth. Univoltine insects with short seasonal flight periods and a limited host range are easiest to control. Annihilation techniques become far more efficacious when using lures that attract females or both sexes, and when they include male-produced pheromones, aggregation pheromones, floral or plant volatiles that serve as ovipositional cues.

Mass trapping and attract-and-kill are cost-effective compared to mating disruption, since much smaller amounts of pheromones are needed. The insecticide component is environmentally rather safe, since small amounts are used and since crop contamination during application is much reduced. Nonetheless, the insecticide component is an obstacle to public acceptability of attract-and-kill methods. Fungal or viral insect pathogens might be used instead, but their slow mode of action and the short field-life of formulations have not been solved.

Practical Use of Mass-Trapping

Brinjal Fruit and Shoot Borer Eggplant is an important vegetable in South Asia, commercially produced by approximately 700,000 farmers on 570,000 ha in India alone. In Bangladesh, 40% of all vegetables produced are eggplants, providing farmers with a regular, year-round income. Severe yield losses are caused by the fruit and shoot borer *Leucinodes orbonalis*. Insecticides appear to be largely ineffective for control of *L. orbonalis*, because of protection offered by the fruit itself and because of insecticide resistance. A pheromone-based mass trapping strategy has been developed, from optimization of the pheromone blend and dose, trap design, and placement to field implementation (Cork et al. 2001, 2003, 2005a). Mass trapping, without the use of insecticides, has led to a 50% and higher increase in marketable fruit, which has been attributed to the combined effects of mass trapping and enhanced impact of natural enemies. Additionally, secondary pests, such as mites and whitefly, were reduced in the pheromone plots. The yield increase translates to earnings of $1,000 US$ per ha and yr for resource-poor families. Given estimated sales of pheromone lures reported in India and Bangladesh (Table 1), at least 15% of all farmers have now adopted the technology, and this is increasing year on year (A. Cork, unpublished).

Bark Beetles Bark beetles are of tremendous importance in coniferous forests worldwide, and the discovery of the aggregation pheromones of the most destructive European and North-American species was soon followed by area-wide mass trapping campaigns (McLean and Borden 1979; Bakke 1982). A more recent study corroborates that mass trapping is indeed a viable control strategy. In an isolated 2,000-ha forest reserve in China, traps for the double-spined spruce bark engraver *Ips duplicatus*, baited with a 2-component pheromone blend of ipsdienol and *E*-myrcenol, were employed at a rate of 1 trap/25 ha for 3 years. Yearly beetle captures between 0.5 and 1.7 million strongly reduced average tree mortality to 17% according to a 20-year record (Schlyter et al. 2003). This particular forest is isolated, but treatments on larger areas that use the same trap density should produce the same effect.

Palm Weevils Palm weevils are the most destructive pests of palm trees and cannot be efficiently controlled with insecticides. Adult weevils are not very susceptible to toxic compounds, and mining larvae are protected inside tree trunks. They provide an outstanding example of sustainable area-wide insect control by mass trapping, covering thousands of hectares of palm in all growing regions, particularly in Central America, the Middle East, and South Asia (Table 1). The beetles use aggregation pheromones for sexual communication prior to mating, attracting both males and females. A facilitating factor is that overall population densities are lower than in smaller insects. Attractancy of the lures can be augmented by the use of plant and associated fermentation volatiles (Giblin-Davis et al. 1996; Oehlschlager et al. 2002).

Males of the American palm weevil, *Rhynchophorus palmarum*, release an aggregation pheromone, rhynchophorol: (4S)-2-methyl-(5E)-hepten-4-ol (Rochat et al. 1991; Oehlschlager et al. 1992). Captures with pure rhynchophorol increase considerably with the addition of plant material, leading to the development of an efficient control method based on mass trapping (Oehlschlager et al. 1993). Laboratory studies corroborate that aggregation is mediated by a male-produced pheromone and host-plant volatiles that include acetoin and ethyl acetate (Said et al. 2005). The American palm weevil is an important pest of several palm species in tropical America. Besides damaging the trees, it vectors a nematode that cause red ring disease. At less than one trap per 5 ha, even high palm weevil populations and nematode infestation rates have been reduced to very low infection levels, after only 1 year of trapping in combination with removal of infected palms (Oehlschlager et al. 2002).

The red palm weevil, *Rhynchophorus ferrugineus* originates in South-East Asia and is now widely distributed in Asia, Africa, and Oceania. It infests a range of tropical palms, including date, oil, and coconut palms. The larvae develop in the tree trunk, where they destroy the vascular system. Tens of thousands of date palm trees have been destroyed in the Middle East and North Africa since its appearance in the eighties because insecticide-based control is not sufficiently efficient (Soroker et al. 2005; Blumberg 2008). Mating in red palm weevil is mediated by an aggregation pheromone produced by the male weevil, composed of the main compound (4S,5S)-4-methyl-5-nonanol (ferrugineol) and 4-methyl-5-nonanone (Giblin-Davis et al. 1996; Perez et al. 1996). Traps loaded with ferrugineol, supplemented with ethyl acetate and plant volatiles, and a fermenting mixture of dates and sugarcane molasses, are placed at densities of up to 10 traps/ha for monitoring and mass trapping. Pheromone traps have played a significant role in the suppression of red palm weevil populations, for example in date palm plantations in Israel (Hallett et al. 1999; Soroker et al. 2005).

Banana Weevil The banana root borer *Cosmopolites sordidus* is a major pest of bananas throughout the world. The male-produced aggregation pheromone sordidin attracts both sexes, and mass trapping by using ground traps has the potential to replace inefficient insecticide treatments (Reddy et al. 2009).

Japanese Beetle The Japanese beetle is a devastating pest of urban landscape plants in the eastern United States and traps are sold in many garden centers. These are baited with a combination of synthetic pheromone, japonilure, and with floral compounds, phenethyl propionate, eugenol, and geraniol. This powerful lure can attract thousands of beetles. However, due to limited trapping efficacy, the spillover onto surrounding host plants is counterproductive, unless traps are placed at some distance from the plants needing protection (Switzer et al. 2009).

Practical Use of Attract-and-Kill

Cotton Boll Weevil The cotton boll weevil *Anthonomus grandis* is a major pest of cotton in the Americas. Males produce an aggregation pheromone, grandlure (Tumlinson et al. 1969), that has been successfully incorporated into a pheromone-baited killing station known as "Boll Weevil Attract and Control Tubes". These tubes are produced in large numbers every year (Table 1). A density of 14 traps per ha achieves a strong reduction in weevil populations, at minimal crop damage. After successful control and eradication programs in the USA, bollweevil trapping is now also used in South America on at least 250,000 ha (Ridgway et al. 1990a; Smith 1998).

House Fly In addition to feeding attractants, house flies *Musca domestica* are attracted to pheromone, (Z)-9-tricosene (muscalure), which is widely used in combination with co-attractants in lure-and-kill approaches indoors and in livestock stables (Table 1; Butler et al. 2007; Geden et al. 2009).

Fruit Flies Male fruit flies (Diptera, Tephritidae) produce pheromones that attract females (Jang et al. 1994; Landolt and Averill 1999). However, these sex pheromones have not been a main research target, because of the efficacy of parapheromones and plant volatiles as attractants (methyl eugenol, trimedlure, cuelure, angelica seed oil, enriched ginger oil, raspberry ketone), and hydrolyzed protein baits (e.g., GF-120). These have been most widely used for monitoring and annihilation of several fruit flies, including Oriental fruit fly *Bacterocera dorsalis*, melon fly *Bacterocera cucurbitae*, and Mediterranean fruit fly, *Ceratitis capitata* for almost 50 years. Methyl eugenol, which is a male pheromone precursor, is a highly effective attractant and is used in IPM programs and for eradication of *Bactrocera* flies by male annihilation in the Pacific region, including Hawaii and California (Cunningham et al. 1990; Hee and Tan 2004; Vargas et al. 2008; El-Sayed et al. 2009).

A female-produced pheromone, a blend of (1,7)-dioxaspiro-[5,5,]-undane (olean), α-pinene, n-nonanal, and ethyl dodecanoate is exploited for control of the olive fly *Bactrocera oleae* by a lure-and-kill technology that incorporates the food attractant ammonium bicarbonate (Mazomenos and Haniotakis 1985; Broumas et al. 2002).

Orchard Tortricids A fully integrated attract-and-kill product, containing 0.16% pheromone and 6% permethrin, has provided control of codling moth at economic levels of less than 1% harvest infestation in apple orchards in Switzerland. Based on reductions in trap catch and the mating frequency of tethered moths, efficacy of the attract and kill droplets lasted 5–7 wk, requiring two seasonal applications. Subsequent experiments replaced permethrin with an alternative toxicant, the insect growth regulator, fenoxycarb, which has a sterilizing effect. Field tests showed that autosterilization, i.e., transfer of the insect growth regulator from a contaminated male to the female moth at mating, contributes to the control effect (Charmillot et al. 2000, 2002).

Studies of competition have shown that attracticide droplets are more attractive to male moths than calling females, and that the number of point sources is key to the ability of males to locate calling females (Krupke et al. 2002). Commercial applications require applications of 3,000 droplets per ha. At this rate, disruption of male orientation is likely to be a contributing mechanism. This has been substantiated with two further key orchard tortricids, Oriental fruit moth *Grapholita molesta* and lightbrown apple moth *Epiphyas postvittana* (Suckling and Brockerhoff 1999; Evenden and McLaughlin 2004).

Disorientation and Communication Disruption by Air Permeation

Insects rely on volatile sex pheromones to communicate for mating. Permeation of the crop with synthetic sex pheromone can disrupt chemical communication and thus prevent mating. Indeed, the mating disruption technique has become the most commonly utilized application of semiochemicals for population control (Baker and Heath 2004; Witzgall et al. 2008). Unlike with mass trapping, the natural pheromone is not required for mating disruption to be effective. Both attractive and non-attractive pheromone blends have been used, since off-blends can result in considerable cost savings (Bengtsson et al. 1994; Cork et al. 1996; Stelinski et al. 2008). Negative signals, including antiaggregation pheromones, have been combined with attractants into push-pull techniques (Borden 1997; Schlyter and Birgersson 1999; Cook et al. 2007).

The behavioral mechanisms by which mating disruption is achieved have been subject to investigation and discussion since Bartell (1982). If we understood the underlying mechanisms that cause or result in the behavioral modification that leads to disruption of mating, we will be better placed to understand why some applications are successful and others not (Cardé and Minks 1995; Sanders 1996, Miller et al. 2010). Attempts to interpret the behavioral response to air permeation treatments should, however, also build on field data on both the behavior of moths and molecules. Male moth behavior depends on a number of factors, including pheromone blend, release rate, and aerial concentration. Measurement of these factors and their contribution to efficacy will help to predict the outcome of mating disruption (Bengtsson et al. 1994).

Resistance to mating disruption is a remote risk in many species, because changes in female pheromone biosynthesis or male response are unlikely to lead to a new communication channel that is unaffected by synthetic pheromone treatments that do not precisely match the female-produced blend. However, resistance to treatments with a single pheromone component has occurred in the small tea tortrix *Adoxophyes honmai*. The efficacy of (Z)-11-tetradecenyl acetate, a ubiquitous leafroller pheromone component, decreased after 16 years. The composition of the pheromone blend produced by the females was unaltered, but the pheromone response was broader in resistant males. Efficacy of mating disruption returned to its former level, after changing to the natural 4-component pheromone blend (Mochizuki et al. 2002; Tabata et al. 2007a, b).

Commercial use of mating disruption became possible only after industrial scale synthesis became available at the end of the eighties. As a general guide, application rates of between 10 g and 100 g per ha per season are required to achieve communication disruption, thus resulting in aerial concentrations of at least 1 ng/m3 (Bengtsson et al. 1994; Cork et al. 2008).

A wide range of controlled release formulations has been developed for use in mating disruption. Early on, it had been assumed that a very high density of point sources was required to produce an effective fog of pheromone to disrupt male moths, and, therefore, formulations such as aqueous suspensions of micro-capsules and hollow fibers were developed. However, with the advent of hand-applied reservoir-type formulations, it was realized that fewer point sources that release higher quantities of pheromone could achieve the same result, by generating plumes with high concentrations of synthetic pheromone. Season-long field life is a main advantage of hand-applied dispensers. Renewed efforts to develop sprayable formulations is motivated by reduced application cost, either in combination with fungicides in orchards, or for applications on large areas (Leonhardt et al. 1990; Weatherston 1990; Trimble et al. 2003; Tcheslavskaia et al. 2005; Il'ichev et al. 2006).

A major flaw of current commercial pheromone dispensers is that pheromone release increases with ambient temperature. In apple orchards treated against codling moth, ca. 90% of pheromone applied is released outside the diel flight period, mainly during daytime at peak ambient temperatures (Witzgall et al. 1999). In addition, dispensers must be applied early in season when population densities are still low and release rates decrease during the season, as population densities start to increase. These problems can be circumvented by using timed and metered pheromone sprayers that release constant and large amounts of pheromone only when the insects are active (Shorey and Gerber 1996; Mafra-Neto and Baker 1996; Fadamiro and Baker 2002). Such "puffers" are now increasingly used against navel orangeworm *Amyelois transitella* and codling moth.

Mating disruption is more efficacious over large areas. This is in part because large areas reduce the impact of gravid females that immigrate into treated plots, but also because homogenous air permeation is facilitated. Incomplete permeation with pheromone, especially along crop borders, is an obstacle. This has been confirmed by field EAG measurements of aerial pheromone concentrations (Milli et al. 1997). Border effects become negligible when large surfaces are treated. Indeed, dispenser spacing and overall pheromone application rate can be reduced as the treated area increases, resulting in considerable cost savings to farmers.

Adoption of mating disruption and reduction of insecticide leads to a decrease in the incidence of secondary pests due to conservation of natural enemies. In orchards and vineyards, mating disruption renders treatments against phytophagous mites superfluous since outbreaks are typically induced by the overuse of insecticides.

Other biological techniques rarely permit stand-alone containment of insects, and mating disruption, in addition to annihilation techniques, is often the only option when insecticides cannot be applied, as in organic crops, allotment gardens, or against insecticide-resistant insect populations (Suckling et al. 1990; Albert and Wolff 2000). From the nineties onwards, the area under mating disruption saw an almost exponential expansion into the first decade of this century (Fig. 2; Brunner et al. 2002; Ioriatti et al. 2008).

Mating Disruption in Vineyards

The history of mating disruption of grape moths in Europe, reviewed by Arn and Louis (1996) and Ioriatti et al. (2008), exemplifies the weight of interfacing research among extension people, growers, and pheromone industries for the development and implementation of this new technology.

The complete identification of the sex pheromones of the key European grape insects as a prerequisite for the development of mating disruption (Arn et al. 1986; Guerin et al. 1986; El-Sayed et al. 1999b) was the incentive for the development of techniques that still are widely used in chemical ecology research, such as the electroantennographic detector (Arn et al. 1975) and a wind tunnel bioassay with quantitative, controlled stimulus application (Rauscher et al. 1984; El-Sayed et al. 1999a, b).

A portable electroantennogram apparatus was designed for live measurements of ambient pheromone concentrations with an insect antenna, and for rapid optimization of pheromone dispenser placement (Sauer et al. 1992; Koch et al. 2009b). Field tents were used to determine the mating status of female moths and critical population densities, above which mating disruption is no longer effective (Feldhege et al. 1995). The latest methodological progress is appreciably simple but facilitates replicated field measurements of the behavioral effect of dispenser formulations or dispenser densities. Insects are released into portable 8.5 m^3 field cages that contain traps with live females and synthetic pheromone. The cages are placed in vineyards, into 20×20 m pheromone dispenser arrays that simulate full-scale vineyard treatments. The plot size is convenient for the investigation of experimental dispenser formulations (Koch et al. 2009a).

Experimental trials in vineyards were expanded to area-wide campaigns by involving plant protection entomologists, growers associations, and pheromone industries (Rauscher and Arn 1979; Neumann et al. 1993; Vogt et al. 1993). The coordination of mating disruption field campaigns is a complex task, indeed: 1,447 growers participated in Northern Italy in 1999 (Varner et al. 2001). By the end of the nineties, mating disruption had led to an area-wide reduction in population densities and it became widely accepted by growers in Germany, Switzerland, and Northern Italy (Fig. 3; Varner et al. 2001). A challenge in these European vineyards is now to develop novel strategies against new pests that are not affected by mating disruption, especially leafhoppers that vector plant diseases (Mazzoni et al. 2009).

Meanwhile, European grapevine moth *Lobesia botrana* has been found in Chile and Napa County, California. In Chile, 40,000 ha now are under mating disruption in an attempt to eradicate the newly established population (V. Veronelli, pers. comm.)

Mating Disruption in Orchards

Pheromone use in orchards concerns mainly the codling moth *Cydia pomonella*, Oriental fruit moth *Grapholita molesta* (Table 1), and lightbrown apple moth *Epiphyas postvittana*.

Lightbrown apple moth *Epiphyas postvittana* is native to Australia and New Zealand. It is a serious threat to agriculture, because of its polyphagous lifestyle on many fruit and ornamental crops and because it is a quarantine pest in many countries. Suckling and Clearwater (1990) demonstrated that a 2-component blend provided better communication disruption than the main compound alone. Mating disruption then was conceived as a strategy to achieve, in combination with a reduced spray program, economically acceptable control in insecticide resistant populations in apple in New Zealand (Suckling et al. 1990; Suckling and Shaw 1995). More recently, efficient population control has been demonstrated in Australian citrus (Mo et al. 2006). Lightbrown apple moth now has been found in California. A mating disruption campaign uses ground-based sprays and hand-applied dispensers (Garvey 2008; Varela et al. 2008).

Codling moth *C. pomonella* exemplifies some main requirements for competitive pheromone use (Brunner et al. 2002; Witzgall et al. 2008). (1) The larvae damage the crop directly, and the economic damage threshold in apple, pear, and walnut is very low. (2) The hatching larvae are difficult to control with insecticides since they immediately bore into the fruit. A most efficient and widely used insecticide, azinphos-methyl, has been banned in many countries due to its acute neurotoxicity. Resistance problems have occurred with several other insecticides (Reyes et al. 2009). New insecticides, including neonicotinoids that provide more specific control than organophosphates are more costly and still harmful to beneficial arthropods (Beers et al. 2005; Brunner et al. 2005; Poletti et al. 2007). (3) Other, stand-alone biological control techniques are not available. (4) Overuse of insecticides is well-known to harm predatory mites and induce phytophagous mites (Waldner 1997; Epstein et al. 2000; Agnello et al. 2003). Miticide sprays are costly; avoiding them balances the cost of the pheromone treatment. (5) IPM was initiated in orchards and vineyards, and much emphasis has been placed on crop protection education. (6) Consumers are more wary of pesticide residues in fruit than in other food. (7) Sustainable pest control helps to reconcile conflicts between urban and adjacent rural areas, and corroborates the contribution of orchards to the aesthetic value of a region. The worldwide orchard area treated with codling moth mating disruption has now surpassed 200,000 ha, corresponding to, for example, almost half of the European orchard area (Table 2; Fig. 2).

Mating Disruption in Forests

Antipheromones and Bark Beetle Control Bark beetles, including mountain pine beetles *Dendroctonus* sp. can convert large regions of boreal and temperate forest from carbon sinks to carbon sources. It is, therefore, urgent to determine whether pheromones and other semiochemicals become effective in suppressing bark beetle outbreaks. Conifer-inhabiting bark beetles have evolved several olfactory mechanisms for finding, colonizing, and killing their hosts, and also for avoiding unsuitable, overcrowded host trees and resistant nonhost trees. The battery of semiochemicals, attractant and repellent, produced by beetles, host plants, and non-host plants is available for the design of innovative control technology (Borden 1997; Schlyter and Birgersson 1999; Zhang and Schlyter 2004; Seybold et al. 2006).

An alternative strategy to mass trapping with attractant pheromones (see above) are push-pull tactics. These combine aerial permeation of forest stands with anti-aggregation pheromone or repellent non-host volatiles with attractant pheromones. Recent tests confirm the potency of the anti-aggregation pheromones verbenone and methylcyclohexenone (MCH) in aerial forest treatments against mountain pine beetle *Dendroctonus ponderosae* and Douglas-fir beetle *D. pseudotsugae*, respectively (Gillette et al. 2009a, b). These compounds also have been combined with pheromone-based mass-trapping in a push-pull fashion, using hand-applied dispensers (Borden et al. 2006, 2007).

Gypsy Moth The largest application of mating disruption over many years is part of the area-wide management of gypsy moth *Lymantria dispar*, an invasive forest insect in the Eastern US. The "Slow the Spread" program has significantly reduced the spread of gypsy moth by detecting isolated populations in grids of pheromone-baited traps placed along the expanding population front. The detected populations are treated by using *Bacillus thuringiensis* or more frequently by mating disruption, by using aerial applications of plastic flakes (Sharov et al. 2002; Tcheslavskaia et al. 2005).

A prerequisite to the success of managing the spread or establishment of invasive insects is the availability of practical methods for detecting low-density populations. Much of the credit for the success of gypsy moth containment efforts is attributed to the availability of pheromone-baited traps that are inexpensive yet highly sensitive (Liebhold and Tobin 2008).

Area-Wide Programs

Natural insect populations are known to fluctuate in large-scale synchrony. Such spatio-temporal fluctuations are particularly conspicuous in unmanaged forest insects, which can defoliate entire regions (Peltonen et al. 2002). Population fluctuations have been largely neglected in horticultural and agricultural insects while conventional insecticides are the dominating management tactic. The knowledge of population changes on a regional scale is, however, vital for pheromone-based pest management programs (Kobro et al.

Table 2 Use of mating disruption and air permeation with pheromones and antipheromones

Species	Main crop	Region	Area (ha)
Mating disruption			
Gypsy moth *Lymantria dispar*	Forest	USA	230.000
Codling moth *Cydia pomonella* [a]	Apple, pear	Worldwide	210.000
Grapevine moth *Lobesia botrana*	Grape	EU, Chile	100.000
Oriental fruit moth *Grapholita molesta*	Peach, apple	Worldwide	50.000
Pink bollworm *Pectinophora gossypiella* [b]	Cotton	USA, Israel, South America, EU	50.000
Grapeberry moth *Eupoecilia ambiguella*	Grape	EU	45.000
Leafroller moths, Tortricidae	Apple, pear, peach, tea	USA, EU, Japan, Australia	25.000
Striped stem borer *Chilo suppressalis*	Rice	Spain	20.000
Other species	Fruit, vegetables		40.000
Total			770.000
Antipheromones			
Mountain pine beetle *Dendroctonus ponderosae*	Pine	USA, Canada	– [c]
Douglas-fir beetle *D. pseudotsugae*	Douglas-fir	USA, Canada	– [c]

[a] Annual estimated codlemone production is 25 tons (Fig. 2)

[b] Usage dropped significantly upon widespread adoption of transgenic cotton varieties

[c] No data available

2003). In addition, landscape ecology affects insect dynamics, and this should be taken into account for more efficient crop protection (Ricci et al. 2009).

Pheromone-based methods have been shown to produce reliable results especially in area-wide programs, and future applications should, therefore, be planned on a landscape level. Geographic information systems (GIS) make it possible to capture, organize and evaluate insect population data and to visualize spatial and temporal fluctuations on a regional scale. Geo-referenced insect monitoring data can, in addition be correlated with relevant parameters such as distribution of the crop and other vegetation, geography, climate, and insect control programs.

GISs are already in use, especially in forest insects, to document geographic variation, predict outbreaks, and to delimit invasive species (Tobin et al. 2004, 2007). The web adds yet another dimension to the analytical power of geographical information systems, as it provides worldwide connectivity. A web-based GIS permits one to quickly disseminate and share information, and it enables interactivity between end users, extension people, and researchers. A rigorous effort should be made to apply such techniques for landscape-level applications of semiochemical-based insect control.

Other Semiochemicals

Semiochemicals that attract insect females are tools for monitoring the occurrence and reproductive status of females. This is particularly important in species in which sexual communication relies on female-produced sex pheromones that attract only males. Moreover, some powerful annihilation strategies are based on female attractants (Table 3). Plant-derived chemicals also are known to improve attraction to pheromone lures (Giblin-Davis et al. 1996; Oehlschlager et al. 2002; Knight and Light 2005; Knight et al. 2005; Bengtsson et al. 2006; Schmidt-Büsser et al. 2009).

Even non-host volatiles may play a significant role in insect management, since some insects avoid volatiles of non-host plants. The know-how of negative plant volatile signals can be used to design push-pull techniques (Borden 1997; Zhang and Schlyter 2004; Cook et al. 2007).

Floral Compounds that Target Moths Floral scents play a key role in the coevolution of flowering plants and their pollinators (Raguso 2004; Bergström 2008). The bouquets of flowering plants, for example, Canada thistle and *Buddleja* butterfly bush, are strong attractants for Lepidoptera, Coleoptera, Diptera, and Hymenoptera (El-Sayed et al. 2008; Guedot et al. 2008). Synthetic floral attractants composed of phenylacetaldehyde and other volatiles, such as β-myrcene are known for several noctuid moths (Haynes et al. 1991; Heath et al. 1992; Landolt et al. 2006). Noctuids also respond to attractants that encode fermenting food sources, such as acetic acid and 3-methyl-1-butanol (Landolt and Alfaro 2001; Landolt et al. 2007).

A highly effective technique to control *Helicoverpa* spp. combines floral attractants and feeding stimulants with insecticide. The blend is sprayed on one out of 36 or 72 rows of a cotton field, thus minimizing the environmental

Table 3 Use of other semiochemicals in insect detection (D) and control by mass trapping (MT) and attract-and-kill (AK)

Species	Lure	Purpose	Region	Lures/year
Horticulture				
Mediterranean fruit fly *Ceratitis capitata*	Trimedlure	MT	Worldwide	3.000.000
Melon fly *Bactrocera cucurbitae*	Cue-lure	AK	South Asia, USA	300.000
Oriental fruit fly *Bactrocera dorsalis*	Methyl eugenol	AK	South Asia, USA	400.000
Agriculture				
Corn rootworm *Diabrotica spp.*[a]	Kairomone	AK	USA	40.000 ha
American bollworm *Helicoverpa armigera* [a]	Kairomone	AK	Australia	10.000 ha
Forestry				
Emerald ash borer *Agrilus planipennis*	Kairomone	D	USA	150.000
Medical entomology				
Sheep blowfly *Lucilia cuprina*	Kairomone	MT	Australia, South Africa	350.000
Tsetse fly, *Glossina pallidipes, G. morsitans morsitans*	Kairomone	AK	Southern Africa	–[b]
Bed bug, *Cimex lectularis*	Kairomone	D	USA, Canada, EU, Australia	50.000
Homes				
Social wasps	Food bait		USA, EU	–
Vinegar fly *Drosphila melanogaster*	Food bait		USA, EU	50.000

[a] Treated surface

[b] No data available

impact of the insecticide component. The attractant primarily targets female moths and removes them from the crop ecosystem prior to oviposition, showing that plant volatiles can be used to control insect populations (Del Socorro et al. 2003, 2010a, b; Gregg et al. 2010). The dispersal activity of insects, which is generally perceived as an obstacle for mating disruption and mass trapping, can be turned into an advantage when using female attractants.

This breakthrough development is based on a paradigm shift, since the attractant does not mimic a particular plant, it is instead a combination of compounds from several plants, producing a supernatural floral blend not found in nature (Del Socorro et al. 2003, 2010a, b; Gregg et al. 2010). Clearly, olfactory space would accommodate different floral attractants, since noctuid moths have been exposed to a changing guild of flowers during evolution. It is conceivable, given a more complete knowledge of olfactory receptor ligands, that such synthetic blends can be created also for other insect species.

Social Wasps Blends of acetic acid, with either butyl butyrate, heptyl butyrate, or isobutanol elicit food-finding behavior in a range of social wasps (Landolt et al. 2000). Lures for these wasps are widely distributed for the home and garden market (Table 3).

Corn Rootworms Diabroticine chrysomelid beetles evolved in the prairie ecosystem with larvae that feed on grass roots and adults that feed on vegetative parts of a broad range of plants, including maize. The western corn rootworm, *Diabrotica virgifera virgifera* is a species that is of particular concern in Europe, since it was introduced into the Balkans (Hummel 2003). Adult beetles are attracted to the volatiles of squash blossoms (Cucurbitaceae), and compulsive feeding and arrestment responses on cucurbit foliage are triggered by cucurbitacin secondary plant compounds (Metcalf et al. 1980). This behavior is exploited in the development of floral-baited traps for monitoring (Toth et al. 2007) and flowable and sprayable bait formulations that contain insecticides for area-wide management (Siegfried et al. 2004; French et al. 2007).

Emerald Ashborer The metallic and bright coloration of the elytra of jewel beetles (Buprestidae) points to the significance of visual cues in mate finding. However, host finding is likely mediated by olfactory cues, since many buprestids oviposit on stressed or dying trees. This has been demonstrated in the genus *Melanophila*, where females, which oviposit on wood of trees freshly killed by fire, can detect substances emitted in smoke from burning wood (Schütz et al. 1999).

The emerald ash borer is a rapidly spreading invasive species in the Eastern USA that kills ash trees. The cooperative emerald ash borer project includes a considerable trapping program (Table 3) for early detection in and around the Great Lakes district. Bark volatiles from green ash *Fraxinus pennsylvanica* contain a range of antennal active sesquiterpenes. Natural oil distillates, containing high concentrations of some of these ash volatiles, are currently used as a lure (Crook et al. 2008; Crook and Mastro 2010 this volume). Emerald ash borer trapping is another example of how even immature technology is adopted, due to the absence of other management tools.

Tsetse Flies African trypanosomiasis is transmitted by tsetse flies *Glossina* spp., that are obligate haematophages. The prospect of eradicating tsetse over large areas has appeared to be a serious possibility because of the development of cost-effective semiochemical-based control technologies, notably odor-baited targets that mimic host odor. The search for further host volatiles is ongoing (Harraca et al. 2009). The best known attractant identified from cattle volatiles and buffalo urine comprises a blend of 3-n-propyl phenol, 1-octen-3-ol, and 4-methylphenol (p-cresol), and a separate dispenser containing methyl ethyl ketone or acetone, (Bursell et al. 1988; Vale et al. 1988). Importantly, the odor-baited targets are treated with a fast acting insecticide, typically deltamethrin, and provide visual cues, typically colored in panels of blue and black, that attract and elicit landing in tsetse flies (Torr et al. 1997). There has been a steady increase in the use of odor-baited targets for mass trapping in Southern Africa, with a concomitant insecticide treatment of cattle. In Zimbabwe, an area-wide vector management program reduced typanosomiasis in cattle from several thousand cases per year to two in 1995 (Lindh et al. 2009; Torr et al. 2010).

Sheep Blowflies Australian sheep blowfly *Lucilia cuprina* and related species are potentially controlled by a rather selective synthetic kairomone attractant (Table 3). Insecticidal control is problematic, because of the demand for residue-free wool and the resistance of blowflies to many insecticides. Fly population changes also are driven largely by climate, rather than by biotic factors, and are expected to increase under likely scenarios of climate change (Goulson et al. 2005).

Traditionally, blowfly traps have been baited with liver and sodium sulfide, but a synthetic kairomone, consisting of 2-mercaptoethanol, indole, butanoic acid, and a sodium sulfide solution is far more effective and selective for *L. cuprina* than the standard liver attractant. More importantly, the synthetic mix can be packaged in controlled-release dispensers to generate constant, prolonged release of the attractant. Field studies have confirmed that kairomone traps are a useful component of a blowfly control program (Ward and Farrell 2003; Urech et al. 2004, 2009).

Outlook

Future applications of pheromones and other semiochemicals depend on the availability of odorants that enable efficient manipulation of mate- and host-finding behavior in insects and other animals. It is now within our reach to facilitate the discovery of relevant chemical signals with emerging molecular tools. An odorant binding protein recently has been used in a "reverse chemical ecology" approach to select oviposition attractant candidate compounds in a mosquito (Leal et al. 2008; Pickett et al. 2010 this volume). The next step towards identifying ligands of odorant receptors is to express them in heterologous cell systems for a high-throughput screening of candidate chemicals, by imaging or electrophysiological techniques (Wetzel et al. 2001; Hallem et al. 2006; Kiely et al. 2007). Another, complementary approach is to use structural chemistry software combined with statistical analyses and thus to calculate a physicochemical odor metric that predicts neuronal responses (Haddad et al. 2008). These methods are still in the experimental stage and classic chemical ecology research will meanwhile deliver results. Continued, goal-oriented research aimed at the identification of behaviorally relevant odorants will continue to bring forth novel insect control methods that contribute increasingly to food and environmental security.

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Mating Disruption as a Suppression Tactic in Programs Targeting Regulated Lepidopteran Pests in US

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Abstract Mating disruption, the broadcast application of sex-attractant pheromone to reduce the ability of insects to locate mates, has proven to be an effective method for suppressing populations of numerous moth pests. Since the conception of mating disruption, the species-specificity and low toxicity of pheromone applications has led to their consideration for use in area-wide programs to manage invasive moths. Case histories are presented for four such programs where the tactic was used in the United States: *Pectinophora gossypiella* (pink bollworm), *Lymantria dispar* (gypsy moth), *Epiphyas postvittana* (light brown apple moth), and *Lobesia botrana* (European grapevine moth). Use of mating disruption against *P. gossypiella* and *L. botrana* was restricted primarily to agricultural areas and relied in part (*P. gossypiella*) or wholly (*L. botrana*) on hand-applied dispensers. In those programs, mating disruption was integrated with other suppression tactics and considered an important component of overall efforts that are leading toward eradication of the invasive pests from North America. By contrast, *L. dispar* and *E. postvittana* are polyphagous pests, where pheromone formulations have been applied aerially as stand-alone treatments across broad areas, including residential neighborhoods. For *L. dispar*, mating disruption has been a key component in the program to slow the spread of the infestation of this pest, and the applications generally have been well tolerated by the public. For *E. postvittana*, public outcry halted the use of aerially applied mating disruption after an initial series of treatments, effectively thwarting an attempt to eradicate this pest from California. Reasons for the discrepancies between these two programs are not entirely clear.

Keywords Eradication · Containment · Gypsy moth · Pink bollworm · Light brown apple moth · European grapevine moth · Aerial application · Disparlure · Slow the spread · Invasive pests

Introduction

Introductions of invasive plant pests into uninfested areas can pose significant economic and ecological threats to natural, agricultural, and urban ecosystems. Many countries have regulations and phytosanitary programs to block entry of exotic plant pests (Gordh and McKirdy 2014), but with the ever-increasing levels of international travel and trade, pests sometimes slip in and found incipient populations. As a result, national plant pest programs typically include components to detect exotic pests and then mitigate potential damages. Depending on the pest and the situation, a variety of mitigation strategies may be employed, from efforts simply to ensure that growers have tools to manage the pests to more comprehensive strategies such as classical biological control, population containment, or eradication (Gordh and McKirdy 2014).

In recent decades, programs to mitigate effects of invasive plant pests have come under increasing pressure to use suppression tactics that entail minimal health and environmental

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risks. These programs are run by government agencies and, depending on the size of the pest population, can last months to years across broad areas. Because people move pests, areas where exotics take hold are often residential rather than agricultural, creating an immediate interface between large-scale pest control operations and the public. Historically, pesticides have been a mainstay of invasive pest programs, dating back to broadcast applications of lead arsenate in the late nineteenth and early twentieth centuries for controlling gypsy moths [*Lymantria dispar* (L.)] and eradicating medflies [*Ceratitis capitata* (Wiedemann)] (Clark and Weems 1989; Spear 2005; White et al. 1981). Public sensitization to area-wide applications of insecticides increased in the decades after World War II, once excessive use of organochlorines such as DDT led infamously to detrimental non-target effects (Carson 1962). Additional concerns arose during subsequent programs such as California's medfly eradication in the 1980's, when bait sprays containing small quantities of malathion were repeatedly applied by aircraft across almost 4000 km^2, much of it residential (Jackson and Lee 1985). Despite this, pesticides continue to be important components of many large-scale pest programs, although both the active ingredients and application methods tend to be more targeted than those of early programs (Bloem et al. 2014; USDA-APHIS-PPQ 2016b). Moreover, regulatory programs continually have sought control methods that are target-specific and do not involve toxins, such as the sterile insect technique (SIT) and mating disruption (Dyck et al. 2005; Knipling 1955).

With the flush of pheromone identifications in the 1970's and 1980's, mating disruption began being investigated as means of controlling populations of invasive Lepidoptera (Cameron 1981). Briefly, populations are reduced by saturating the air with a species' sex attractant pheromone to a degree necessary to impede the ability of males to locate females, thus reducing the incidence of mating. Mechanisms and uses of mating disruption have been reviewed elsewhere (Cardé 2007; Cardé and Minks 1995; Ogawa 2007), although specific advantages and disadvantages of the technique bear mention in relation to invasive pest programs. One advantage is that lepidopteran pheromones generally have very low mammalian toxicity, to the degree that the U.S. Environmental Protection Agency (EPA) reported in 2001 that there had been no known incidents of pheromone-caused health issues in humans (EPA 2001). This safety record should, in theory, help allay public fears about possible health effects of broad-scale pest suppression treatments (Soopaya et al. 2015). A second advantage is that, while some pheromone components are shared across a number of moth species (El-Sayed 2014), mating disruption in general has minimal non-target effects and, for example, would rarely be expected to disrupt existing biological controls or food webs (Campion and Hosny 1987; Critchley et al. 1985; Westigard and Moffitt 1984). EPA registration procedures are, accordingly, more streamlined for pheromone-based formulations than for toxin-based insecticides (EPA 2001, 2016), and any required environmental assessments related to programmatic use of pheromone formulations also tend to be simplified. A key disadvantage of mating disruption is that it also reduces the ability of males to locate pheromone-baited traps, which are a mainstay of population monitoring in many moth management programs.

The ability of pheromone treatments to reduce mating appears universally to be inversely related to the density of the target population, although the upper end of pest density where the technique is effective varies among species (Cardé 2007). The relation of pest density to efficacy can be a two-edged sword for programs targeting invasive pests. Populations often are sparse at least in a part of the program area when containment or eradication of a pest is the goal, but the technique could be ineffective in areas where populations are high or in an outbreak condition. Perhaps because of the lack of efficacy against dense populations, some people – including some scientists – seem to consider mating disruption a "soft" control measure and specifically not a viable alternative for suppression where eradication is the goal (Carey and Harder 2013). Admittedly, there is not a wealth of data – either experimental or programmatic – that specifically address the use of the technique as sole or primary eradication tactic. Additionally, while mating disruption has been the subject of numerous modeling studies (e.g., Barclay and Judd 1995; Byers 2007; Yamanaka 2007), models typically have not evaluated the technique in the context of eradication (but see Yamanaka and Liebhold 2009). In practice, as populations becomes more sparse, a female's total potential mates will decrease, while mean distance to the nearest potential mate would (in most cases) increase in both space and time. These factors should lead to a proportional increase in the effectiveness of mating disruption as population density declines, a conclusion that is supported by the available empirical data (e.g., Carpenter et al. 1982; Schwalbe and Albright 1981). In insects, an inability to find mates is considered one of the primary mechanisms of Allee effects, which can cause growth rates of very small populations to turn negative, leading to eventual extinction (Liebhold and Bascompte 2003; Robinet et al. 2008; Taylor and Hastings 2005). As mating disruption will exacerbate mating-related Allee effects and becomes increasingly effective as populations decline, it has been gaining increasing attention as an eradication tool (Blackwood et al. 2012; Brockerhoff et al. 2012; Soopaya et al. 2015; Suckling et al. 2012c; Yamanaka and Liebhold 2009).

Here, we describe and compare four programs where the US Department of Agriculture and cooperating agencies used, or planned to use, mating disruption in eradicating or limiting the spread of an invasive moth pest. These programs vary in their strategic use of mating disruption, formulations and application methods, types and diversity of habitat treated, programmatic goals, and outcomes. Collectively, they demonstrate that mating disruption can be an effective tool for suppressing moth populations in area-wide programs, but that there can also be pitfalls that limit the technique's use.

Case Histories

Pink Bollworm The pink bollworm (PBW) *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) is an Asian moth that was introduced into Mexico around 1911, apparently in shipments of seeds from India (Noble 1969). The insect feeds almost exclusively on cotton, reducing both yield and quality. It was the key pest of cotton in southwestern US and northern Mexico for many years (Walters et al. 2009). The sex attractant pheromone of PBW was identified as a 1:1 mixture of (*Z,Z*)- and (*Z,E*)-7,11-hexadecadienyl acetate (Bierl et al. 1974; Hummel et al. 1973).

The PBW was one of the earliest insects to be targeted with mating disruption. Initially, a pheromone analog, (*Z*7)-hexadecenyl acetate, was shown to be effective in reducing mating frequency when hand-applied to relatively small areas (4.8 ha) (Kaae et al. 1974). In 1974, greater biological activity was demonstrated by using the synthetic pheromone (dubbed "gossyplure"), formulated in hollow fibers, than had been achieved with the analog (Gaston et al. 1977; Shorey et al. 1976). In 1978, after the EPA granted the first registration of a sex pheromone product to Albany International, Cambridge, MA, for the hollow fiber gossyplure formulation (Brooks et al. 1979), approximately 20,000 ha of cotton in the US Southwest were treated with it. The formulation consisted of hollow polyacetyl resin fibers containing pheromone, which were mixed with glue to adhere to foliage and applied by hand or by specially designed applicators attached to aircraft (rights now owned by Scentry Biologicals, Billings, MT, USA). In 1979, the EPA granted an experimental use permit to the Laminate Flake formulation (Hercon Environmental, Emigsville, PA, USA), allowing 192 ha of cotton to be treated with it (Kydoneius and Beroza 1981). The flakes consist of sandwiched layers of semi-porous plastic that enclose the pheromone. Flake size and other parameters can be varied to achieve a required release rate, number of point sources, and application rate (active ingredient per ha). The flakes require specialized equipment for aerial application or can be applied by hand. In 1981, a total of 50,000 ha of cotton was treated with Hollow Fiber or Laminate Flake. In 1982, farmers in California's Imperial Valley voted to use pheromones in the entire valley to reduce pesticide use, about 14,700 ha of cotton.

Two additional types of PBW formulations have been used commercially (Campion et al. 1989; Staten et al. 1987). Microcapsules, where tiny polyurea spheres enclose pheromone, were developed by ICI Agrochemicals in the UK. The spheres are formulated in a water-based suspension that can be sprayed with conventional equipment, and, in cotton, can show excellent rain-fastness even without adhesives. The fourth formulation is a hollow twist-tie dispenser developed by Shin-Etsu Chemical Co. (Tokyo, Japan). The dispenser, or "rope," is a polyethylene tube containing pheromone and a soft wire stiffener, and is twisted by hand around a plant stem. Alternately the rope can be twisted around a stick that then is placed in the ground by hand or machine. In all four products, the pheromone is associated with a solid, which allows for numerous point sources in the field. An alternative formulation was developed that incorporated the pheromone into a liquid matrix, but it never reached the market (Walters et al. 2011).

Development of effective mating disruption for PBW has faced a number of challenges. Ultraviolet light can cause isomerization of components of many pheromones (Ideses and Shani 1988), but in the case of PBW, the resulting isomers inhibit attraction. To minimize degradation, stabilized pheromone formulations containing ultraviolet screeners and antioxidants were devised (Campion et al. 1989). Other difficulties have been: short field life of pheromone, or continuous degradation of attraction; the need for crop isolation so that gravid PBW females don't emigrate from untreated area to treated fields; the pheromone is at the wrong height to interrupt mating, since mating occurs at the top of the plant, and canopy height is dynamic, while applied pheromone height is static; the pheromone may be difficult to acquire if production is not as high as demand; or the pheromone is cost prohibitive to growers.

From 1990 to 1995, a 10,000-ha PBW suppression study was undertaken in Parker Valley, AZ, USA initially using Shin-Etsu Rope and Nomate Hollow Fibers along with limited applications of other chemical insecticides (Antilla et al. 1996). Through the study, the Rope applications were phased out, and the numbers of ultra-low volume insecticide treatments were reduced. The Nomate Hollow Fibers were produced at that time by Ecogen and were mixed with Biotac adhesive and the pyrethroid insecticide permethrin, resulting in an "attract and kill" formulation rather than straight mating disruption. Attract and kill depends on the pheromone to attract the insect for contact with the lethal point source of insecticide. The fibers were applied early season, and, if needed, again later in the season. This study reduced larval occurrence in boll samples from 23 % to less than 1 %, and conventional insecticide use in the region fell from 87,400 cumulative ha treated per season – where most areas had been treated numerous times – to 809. Growers' PBW control costs were cut in half.

In 1994, the initial steps were taken toward the current effort of eradicating PBW from the southwestern US and northern Mexico. Mating disruption was by then an accepted method of PBW control for pest management programs in several countries, and was especially efficacious when used on an area-wide basis, as it would be for eradication (Campion et al. 1989; Critchley et al. 1985, 1991; Staten et al. 1997). In addition, the sterile insect technique had proven effective against PBW, and a large rearing facility had been built in

Arizona (Staten et al. 1993). From 1994 to 1998, beginning in Imperial Valley, CA, USA and later including Palo Verde Valley, CA, USA, the PBW project monitored cotton with pheromone baited traps, released large numbers of sterile PBWs, blanketed cotton with pheromones for mating disruption, and used a minimum of insecticides (Walters et al. 1998). In 1997–1998 Bt cotton varieties became available, which further enhanced the overall effectiveness of PBW suppression efforts. In 2001, Texas joined the PBW Eradication Program, treating 15,000 ha of cotton. This was followed in 2002 by New Mexico, where treatments began on 4300 ha of cotton, and in 2006 Arizona began treating 77,400 ha of cotton in the PBW Eradication Program. In the San Joaquin Valley of California, the control program has kept PBW from becoming established for many decades, beginning with sterile moth releases in the 1970s, along with early use of pheromones for trap monitoring and later mating disruption. California currently maintains 109,265 ha of cotton within the PBW Eradication Program.

Since 2008, no PBW larvae have been found in the southwestern United States and northern Mexico. In the Area-Wide Post Eradication Program, careful pheromone trap monitoring continues, and low level sterile moth production is maintained, to be ramped up quickly in case of PBW re-infestation.

Gypsy Moth The gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Erebidae), is a polyphagous, univoltine forest defoliator that is a major pest of oak and other hardwoods in its native range of Asia and Europe. There are three recognized subspecies: the European gypsy moth *L. d. dispar*, the Asian gypsy moth *L. d. asiatica*, and the Japanese gypsy moth *L. d. japonica* (Pogue and Schaefer 2007). Unlike the other two subspecies, females of the *L. d. dispar* generally have been considered incapable of sustained flight, although this distinction is not always clear-cut (Keena et al. 2008). In addition, the two Asian subspecies reportedly have an even broader host plant range than *L. d. dispar* (Baranchikov and Montgomery 1994).

European gypsy moths were inadvertently introduced into Medford, Massachusetts, USA in the late 1860's by the French naturalist, Étienne Léopold Trouvelot (Forbush and Fernald 1896; Trouvelot 1867), leading to one of the longest battles of government agencies against an exotic insect. Noticeable defoliation began within 10 generations (years) in the vicinity of the escape, and major control efforts, including apparently the first attempt to eradicate an exotic insect pest, were launched in the late 1880's (Forbush and Fernald 1896; Kean et al. 2016; Spear 2005). Despite these efforts, gypsy moth continued to thrive and spread because of the abundance of favored host (oaks) in deciduous forests of eastern North America (McManus and Csóka 2007; Spear 2005). Ensuing programs to limit the spread and minimize damage have included comprehensive and in some cases pioneering efforts in insecticide use, classical biological control, the first use of quarantines to contain a pest population in the US, trapping-based pest detection methods, use of trap data to drive decision algorithms for population management, microbial control (Bt, nuclear polyhedrosis virus), use of sterile insect technique to eradicate a moth, and behavior-based controls such as mating disruption (Doane and McManus 1981; Mastro et al. 1989). The gypsy moth has spread slowly in the US, where after >140 years, almost two-thirds of the area with susceptible hosts is still free of the pest. The current range extends from Minnesota and SE Canada down through Virginia. The insect's slow spread is in part because females in North American populations are incapable of sustained flight (Keena et al. 2008), but there also have been human efforts to limit spread (see below). Damage from the insect in the U.S. was highest from the late 1970's through the early 1990's, with peaks of >5 million ha defoliated in 1981 and 3 million in 1990 (McManus and Csóka 2007). Defoliation cycles have since dampened somewhat, probably in part due to a fungus, *Entomophaga maimaiga*, which became prevalent in North American gypsy moth populations in the 1990's (Hajek 1999).

After a false start (Jacobson et al. 1960), the female-produced sex attractant pheromone was identified as *cis*-(7,8)-epoxy-2-methyloctadecane (Bierl et al. 1970). The $7R,8S$ enantiomer (known as (+)-disparlure) subsequently was found to be the active component, with the (−) enantiomer acting as an inhibitor (Iwaki et al. 1974; Plimmer et al. 1977). Field trials of gypsy moth mating disruption started in 1971 (Cameron 1981). Because researchers assumed that broad tracts of forests often would have to be treated, emphasis from the start was given to formulations that could be applied by aircraft. In addition, smaller-scale field assays were used to answer specific questions, such as a demonstration that racemic and (+)-disparlure are basically equivalent in their ability to disrupt mating (Plimmer et al. 1982). The ability of racemic disparlure to disrupt mating is critical, as the cost of (+)-disparlure remains prohibitive for that use (>$300 USD/g). Over time, a wide variety of formulation types were tested, ranging from pieces of hydrophobic paper and granulated cork to more technological solutions such as microcapsules (gelatin capsules and polymeric beads), hollow fibers, and flakes of laminated plastic (Cameron 1981; Kolodny Hirsch and Schwalbe 1990; Thorpe et al. 2006). In the 1980's, larger-scale work focused on using three-layer laminated plastic flakes (Hercon's Disrupt II, applied with a sticker) as that was the only formulation registered by the US EPA. It also tended to yield more consistent results than those from the various microcapsule or bead formulations. Gypsy moth mating disruption testing is still ongoing, with recent trials focusing on biodegradable alternatives to plastic flakes. These have included a biodegradable polymer flake (Hercon) and a wax-based formulation (SPLAT GM, ISCA Technologies, Riverside, CA, USA) that has proven comparably effective to plastic laminate flakes for a period of 10 weeks after application (Onufrieva et al. 2010).

Current U.S. programs against gypsy moth include three strategies that complement one another but differ in geographic location and objectives. USDA's cooperative gypsy moth programs include a suppression strategy in the generally infested area to reduce damage caused by outbreaks, a barrier zone strategy called Slow the Spread (STS) in the transition area to slow the rate of spread from the generally infested area, and an eradication strategy in the uninfested area to prevent establishment of isolated infestations well outside of its established range (USDA 1995, 1996, 2012a, 2012b). Two USDA agencies, the Forest Service (FS) and the Animal and Plant Health Inspection Service (APHIS), share responsibility for oversight and implementation of these programs in cooperation with state agencies. In general, FS oversees suppression and STS, while APHIS oversees eradication and regulates areas where the moth is present in an effort to minimize human transport of the pest into uninfested areas. APHIS and cooperating state agencies also maintain a trapping network to detect and eradicate any populations that become established well beyond the known generally infested area.

APHIS and state cooperators also maintain intensive arrays of traps in port areas, specifically to monitor for Asian gypsy moths (in the broad sense, including both Asian subspecies of *L. dispar* plus several Japanese sibling species that respond to (+)-disparlure) (USDA-APHIS-PPQ 2014). Because of female flight and their apparently wider host range, these taxa are, for regulatory purposes, considered a higher risk and a separate entity from the population of *L. d. dispar* that is already established in the U.S. Incipient populations with flighted females have gained a foothold at times in the Carolinas, British Columbia, and the Pacific Northwest, but have been eradicated or are under eradication (USDA-APHIS-PPQ 2014).

Development of treatments used to control gypsy moth were historically driven by the need to control outbreak populations in suppression programs. In the past two decades, *Bacillus thuringiensis* var. kurstaki (Btk) and insect growth regulators have been the primary treatments in both suppression and eradication because they give good results when used against all population densities. Other tactics such as mass trapping, sterile insect release, and mating disruption are effective only in low density populations, and they never have been used in suppressing outbreaks. Relative to many other moth species, mating disruption in gypsy moth requires very low population levels to be effective, perhaps due to the males' active flight and effective short-range searching behaviors (Cardé 2007; Charlton and Cardé 1990). Despite this, the tactic has been used alone or in conjunction with Btk in several eradication projects. As noted above, species-specificity and minimal toxicity make mating disruption a good choice for urbanized and environmentally sensitive areas, but effects on trap catch have slowed its acceptance as an eradication tool. Disparlure treatments virtually eliminate the ability of regulatory agencies to conduct trap-based monitoring of target populations during the control phase of gypsy moth eradication projects.

By far the most extensive use of mating disruption against gypsy moth is in the STS program where almost 3 million ha have been treated using this tactic since STS became operational in 2000 (USDA 2016). Mating disruption is used on about 80 % of the area treated as part of STS because it is effective, environmentally benign, inexpensive, and generally accepted by the public.

The national STS program (2000-present) was preceded by a pilot project (1993–1999) on 3 million ha in the states of North Carolina, Virginia, West Virginia, and Michigan. The pilot project demonstrated the feasibility of using a barrier zone strategy to reduce the rate of spread by more than 60 % through intensive monitoring with systematic grids of pheromone-baited traps and treatment of detected populations (Sharov et al. 2002). The benefits of reducing the rate of spread of gypsy moth exceed the costs of treatment and monitoring by a ratio greater than three to one (Leuschner et al. 1996; Mayo and Leonard 1997; Sills 2008).

Currently, STS is implemented in a band 100 km wide that adjoins the generally infested area (Sharov and Liebhold 1998). This band is called the transition area because gypsy moth populations are "transitioning" from continuous, as they exist in the generally infested area, to isolated, as they are in the area that is not yet infested (Fig. 1). Gypsy moth populations in the transition area are characterized as recently established, generally still at very low densities, and still separate from one another. Areas proposed for treatment as part of STS are selected with the aid of a decision-support system (Tobin et al. 2004) that uses data from about 70,000 traps in the transition area to select, analyze, and prioritize hundreds of infestations that are proposed for management each year (Fig. 1).

Prior to the initiation of STS, treatment programs to control gypsy moth were targeted primarily at outbreak populations in the generally infested area. As such, mating disruption was seen as an interesting research question but there was no real niche driving its development for operational use. The need to treat the low density populations found within the STS area fueled the technology development required to bring mating disruption into the operational arena by the time STS became a national program in 2000.

When the STS pilot project was initiated in 1993, Hercon's Disrupt II was the only disparlure formulation registered with the US EPA, and the only dose that had provided consistent results in small trials was 75 g AI (disparlure) per ha (Webb et al. 1988). The initial task was to demonstrate through repeated trials that 75 g AI/ha would disrupt mating sufficiently to control or eliminate the low density populations found in

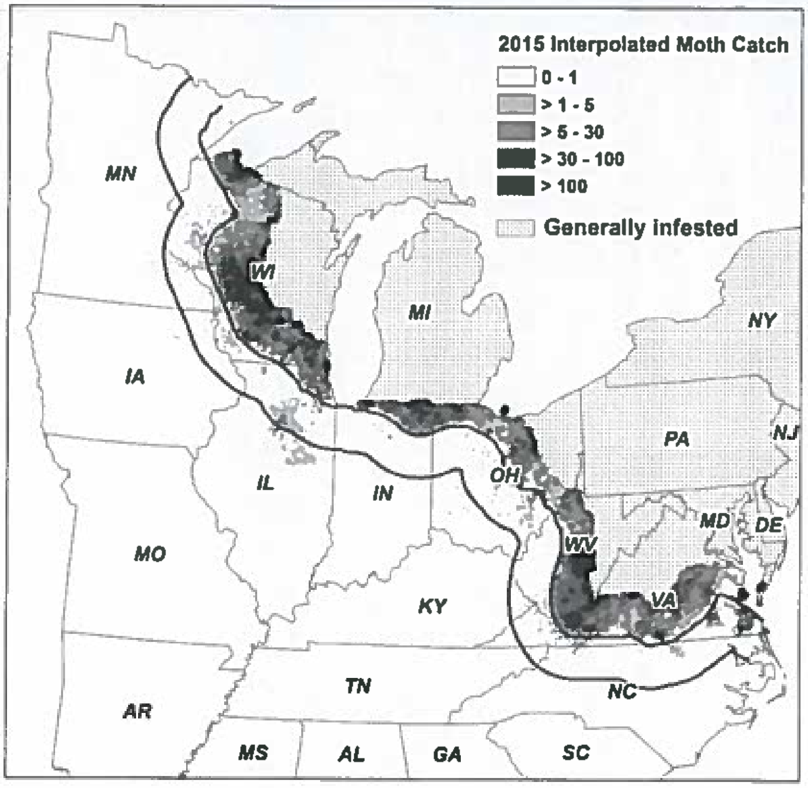

Fig. 1 Surface interpolations of moth captures in pheromone traps across the leading edge of gypsy moth populations. The Slow the Spread (STS) program area is outlined by the two thicker lines

the STS project area. Criteria for success were defined as minimums of (1) a 90 % reduction in captures at pheromone-baited traps, and (2) 95 % reduction in the mating of females when compared to untreated control plots over an 8 to 10-wk. period. User confidence in the technique was low initially but increased as multiple field trials demonstrated successful disruption of mating in low-density populations using a single application annually of Disrupt II (Leonhardt et al. 1996; Thorpe et al. 2006). As user confidence went up, operational use of mating disruption in the STS pilot project increased from just a trace in 1993 (1225 ha) to >50 % of the area treated in 1999 (16,000 ha) and, eventually >80 % of the area treated in the national program from 2000 to present (average of 182,000 ha per year).

Once the efficacy of mating disruption had been well documented, the focus changed to other problems associated with the tactic. The most pressing among these were (1) poor performance of the custom application system for the flakes (pods) used on aircraft, (2) high costs associated with high dosages, limited use, and custom application systems, and (3) a quest for a formulation with a more efficient release profile that could be applied through conventional spray systems. These issues were addressed in the final years of the pilot project (1998–1999) and the first few years of the national program (2000–2003).

Applications of Disrupt II were initially conducted using wing-mounted pods that were developed in the 1970s by Schweitzer Aircraft to apply the PBW Hercon flake product at a much lower rate. The flakes were dispensed through an auger, then mixed with sticker and dispersed via a fan-like "spinner." The pods, which were mounted under the wing of a Cessna 206, were troublesome from the start (Thorpe et al. 2006). The augers could not deliver sufficient quantities of flakes for the desired dose, the hoppers were small, the motors for pod's augers and sticker pumps were unreliable, and uneven flow (bridging) of the flakes feeding from the hopper was problematic. These problems led to unacceptable production rates of <50 ha/h/aircraft. Eventually the Forest Service entered into contracts with aerial applicators to develop an improved delivery system. Two new systems were designed and tested, but a modified pod ultimately proved to be the best solution. Larger hoppers were constructed, new motors with electronic controllers were installed, and the new pods were mounted on larger, turbine-powered aircraft that were designed for aerial application – primarily Air Tractors. Hercon added diatomaceous earth to the formulation, which solved the bridging problem. By 2002, production rates on projects were up to 300–350 ha/h/aircraft, and recently have leveled out around 450 ha/h/aircraft. Without these improvements, application of Disrupt II could never have become cost-competitive with liquid treatments such as Btk, which are applied using conventional spray systems.

The next issue that had to be addressed was the cost associated with high dosages. Dose response tests in 2000 showed no significant difference between the 75 and 37.5 g AI/ha doses, and additional tests through 2002 found positive dose-response relationship between mating disruption and six disparlure dosages (0.15, 0.75, 3, 15, 37.5, and 75 g AI/ha) (Tcheslavskaia et al. 2005). Accordingly, doses on operational treatments were reduced to 37.5 g AI/ha in 1999 and reduced again to 15 g AI/ha in 2002. The reduction in operational doses coincided with the transition from a 3 million ha pilot project to the 26 million ha national STS program area in 2000. Total area treated continued to increase further each year as the program area grew. The increase in area being treated combined with lower dosages and a better application system resulted in significant reductions in the cost (pheromone + formulation + application services). In 1993, treatment of 1225 ha cost >$200/ha USD for the 75-g AI/ha dose; in 2002, >225,000 ha were treated for less than $25/ha.

An ideal formulation of disparlure would be sprayable through conventional systems, release pheromone at a constant rate, and discharge all of its AI over the 8–10-wk. period between application and the conclusion of male flight and mating activity. In contrast, Disrupt II still requires custom application systems; it releases pheromone at a constant but slow rate, losing only 30–50 % of AI during the flight and mating period (Leonhardt et al. 1996; Thorpe et al. 2006). As the area being treated with mating disruption increased, there was renewed interest in the market to produce controlled release formulations of disparlure. A variety of candidate formulations (microcapsules, hollow fibers, granules, sprayable liquids, microflakes, bioflakes, and a wax based polymer matrix) have been screened. None of the candidate formulations could be applied using conventional systems, but most were thought to be more efficient releasers of pheromone than Disrupt II, which theoretically could lead to further reductions in dose and cost. Although all of the formulations shut down male moth captures for some period of time, most released their pheromone too rapidly to cover the desired 8–10-wk. period with a single application. Of all the formulations screened, only Disrupt II and the wax based polymer matrix SPLAT (ISCA Technologies, Riverside, CA, USA) produced acceptable shut down of male captures for 8–10-wk. with a single application.

The STS program uses a variety of treatments to control gypsy moth. Btk, nuclear polyhedrosis virus, and growth regulators are used to target the higher density populations (generally areas with >100 moths per trap), while mating disruption is used to target the lower density populations. Pheromone traps are used to detect and delineate incipient populations that require treatment, to provide data for planning and prioritizing actions, and to evaluate the success of treatments that are applied (Tobin et al. 2004). An index of treatment success, which measures the reduction in moth counts in the block treated adjusted by the change in moth counts in the reference area around it, is used to evaluate all treatments in STS (Sharov et al. 2002). From 1993 to 2015, more than 4000 treatment blocks totaling almost 3.5 million ha have been evaluated. The success rate of mating disruption treatments averages 85 % and compares favorably with the success rates of other treatment types, which are mostly Btk (75–80 % depending on the year).

Currently Disrupt II and SPLAT-GMO are both used for operational mating disruption treatments in STS. Although neither satisfies all the criteria for an "ideal" formulation, both effectively disrupt mating for 10 wks with a single application. Treatments have been conducted over millions of ha including wilderness areas, National Parks, and highly urbanized areas such as Chicago, Illinois and Columbus, Ohio, with very few issues from the public or from government agencies concerned with protection of rare, threatened, or endangered species or their critical habitats (USDA 2016). With that said, Hercon has been working toward organic replacements for the flakes in Disrupt II, as there has been growing concern over pollution by small and micro-sized plastic particles, especially in aquatic environments (Ivar sul and Costa 2014). The ability to treat widespread areas with a gypsy-moth-specific tactic such as mating disruption has been critical to the success of STS in slowing the rate of spread from historical rates of 21 km per year to less than 8 km per year (Tobin and Blackburn 2007).

Light Brown Apple Moth The light-brown apple moth (LBAM), *Epiphyas postvittana* (Lepidoptera: Tortricidae) is a highly polyphagous leaf-roller native to Australia (Danthanarayana 1975). The species is a pest of numerous fruit crops in its native range, including, among others, pome fruits, stone fruits, grapes, citrus, and cane berries. In addition, LBAM can be present in foliage of a large number of plants that are traded as nursery or flower commodities, which creates substantial regulatory risk (Brockerhoff et al. 2011; Suckling and Brockerhoff 2010). LBAM is a proven colonizer and has established in New Zealand, Great Britain, Hawaii, and, more recently, California (Suckling et al. 2014). In Australia and New Zealand, the moth historically has been a pest of great concern and, as such, the subject of extensive research and development on pest management practices (Suckling and Brockerhoff 2010). The identification of a sex-attractant pheromone for LBAM was reported in 1983: (*E*11)-tetradecenyl acetate and (*E*9,*E*11)-tetradecadienyl acetate in a ratio of approximately 20:1 (Bellas et al. 1983). More recent investigations have identified additional minor components, (*E*11)-tetradecan-1-ol and possibly (*E*11)-hexadecenyl acetate (El-Sayed et al. 2011).

In early 2007, Dr. Jerry Powell, a retired UC Berkeley entomologist, reported catching two LBAM in a back-yard light trap in Albany, CA, USA (Suckling and Brockerhoff 2010). As LBAM was considered a high-priority pest by USDA and had been included as a targeted pest in the US Cooperative Agricultural Pest Survey (CAPS) program, an ad-hoc group of advisors was assembled, and they recommended an intensive detection and delimitation effort. The trapping quickly determined that the moth was present from south of Monterey Bay through much of the San Francisco Bay area, with relative hot spots around the cities of Santa Cruz and San Francisco (Suckling et al. 2014).

A full Technical Working Group (TWG) of experts from USDA, universities, and two foreign countries (Australia and New Zealand) was assembled. After some deliberation, the TWG recommended attempting to eradicate the population, with the conditions that cost-benefit analyses supported the program, effective control tools remained available for use, and the population did not grow or spread to the point where eradication appeared highly unlikely (USDA-APHIS-PPQ 2007). The recommendation was based in large part on reports that LBAM was a significant agricultural pest within its native range and had become arguably the most serious horticultural pest in New Zealand before classical biological control efforts and associated IPM practices had made it more manageable (Varela et al. 2010b). In addition, LBAM is a pest of regulatory concern and thus affects market access for some major commodities (Danthanarayana 1975; Suckling and Brockerhoff 2010).

The TWG recommended an integrated approach to controlling the pest, while relying on mating disruption – applied by aircraft – as the primary suppression tactic (USDA-APHIS-PPQ 2007). Mating disruption had been thoroughly studied in LBAM and demonstrated to be effective on populations that produced trap captures that were within the range being recorded in California (Mo et al. 2006; Suckling and Clearwater 1990; Suckling and Shaw 1995). As discussed above, once a population has been reduced to a level where mating disruption is effective, the inverse density dependence of the tactic should theoretically lend itself to completing the eradication process. The TWG knew that the geographic area occupied by the population was approaching the limit of what could reasonably be tackled for eradication in this context and that much of the area was residential. Aerial application would be needed, although mating disruption for LBAM had previously relied almost exclusively on hand-applied and "puffer" formulations. In addition, Californians were known to be averse to aerial spraying of toxins (Jackson and Lee 1985). In contrast, however, aerial dispersal of sterile insects is readily tolerated, and the TWG considered that mating disruption was another essentially non-toxic and highly species-specific control method.

The newly assembled program for LBAM eradication took the recommendations and rapidly moved toward implementation. Two types of formulations were potentially available for aerial application: one was based on microcapsules, and the other was Hercon's laminated flakes. Although the flakes had been deployed against gypsy moth with minimal complaints and across broad areas over various habitats, including residential areas, program personnel chose not to use that formulation over concerns that it could violate local plastic pollution laws. That left the microcapsules as the only choice in the short term.

During the fall of 2007, almost 15,000 ha in Monterrey County, CA, were treated twice within 6 weeks, and an additional 21,000 ha were subsequently treated in Santa Cruz County (USDA-APHIS-PPQ 2008b). The TWG reconvened in the fall of 2007 and concluded that the observed disruptive effect was not sufficient in either magnitude or longevity to warrant further treatments until improved formulations were available (USDA-APHIS-PPQ 2008a). There were a number of factors that, in combination, could have been responsible for the low treatment efficacy. First, the attractant is a relatively small pheromone compound (14 carbon base) and, with a microcapsule formulation, may have been released too rapidly (Brockerhoff et al. 2012). Additionally, apparently to reduce possible conflicts with the public, the material was applied without a sticker, and, due to regulations on overflight of residential areas, applications were made from a much higher altitude (150+ m) than would be typical in an agricultural application. Finally, the minor component of the pheromone was not available in quantity early on, so the first Monterrey application was made with only the major component, (*E*11)-tetradecenyl acetate.

The TWG and program personnel outlined a test to identify a more effective formulation – a replicated field trial with aerial applications to relatively uniform blocks. The only place that was readily available and had the necessary combination of moth populations, space, expertise, and infrastructure was a *Pinus radiata* plantation on New Zealand's South Island. The test was run from February through June 2008. Four companies submitted formulations for aerial (helicopter) application and evaluation; controls included untreated blocks and blocks treated with hand-applied Isomate twist-ties (Shin-Etsu Chemical Co., Ltd., Tokyo, Japan), known to be effective against LBAM. The two formulations that were not based on microcapsules proved effective enough that the TWG recommended them for programmatic use (Brockerhoff et al. 2012). One consisted of organic chips from Hercon, which were applied with a sticker, similar to their laminated plastic flake formulation; the other wax-based formulation (ISCA's SPLAT) was pumped out through open tubes (no nozzles) and formed small drops that adhered to foliage.

In California, complaints from the public, including several organized groups, had started with the initial spraying in the Monterey area, and they continued to escalate through the time of the New Zealand tests. Over 600 complaints had been received by a California Department of Food and Agriculture (CDFA) call center and several web sites during the spraying (463 once duplicates and non-human issues were eliminated). Most complaints expressed concern over possible health effects and descriptions of mild respiratory or digestive symptoms that people thought might be associated with the sprays (OEHHA 2008), but there were also some claims of more serious reactions (Carey and Harder 2013). Once communicated by the press, it was often "over 600 people were sickened by the sprays," although cause and effect was not established in any case and was considered unlikely when viewed objectively (NRDC 2007; OEHHA 2008).

Groups against the program had developed a significant internet presence that the public affairs branches of USDA and CDFA had not previously experienced. Opposition groups could instantly post materials with any claims or comments – valid or not – whereas USDA and CDFA responses had to be written and then reviewed on several levels, taking days or often weeks before being released. Some early complaints involved being sprayed with "pesticides" (per labeling, with associated warnings, required by US EPA) or "hormones," but most of the concerns quickly focused on the nature of the formulation itself and its inert ingredients. Proprietary information on the ingredients was leaked to the press (Abraham 2007), and subsequent discussions often exaggerated and/or fabricated information on the associated dangers. An example is characterizing the mixture's small amount of BHT (butylated hydroxytoluene, an anti-oxidant and common food additive) as "carcinogenic, hepatotoxic, tumorigenic, mutagenic, and teratogenic in animals as well as in human cells" (Matthews and Matthews 2008; Sigma-Aldrich 2015; Upton 2008). In addition, a widely distributed analysis concluded that the particulate matter in the spray represented a health risk (Knepp and Haferman 2008). According to the analysis, the amount of <10 μm particles put into the air by an application would have approached the EPA's once-per-year maximum for 24-h average concentration (EPA 2012). The analysis, however assumed the entire mass of the formulation was particles (>70 % was water) and also assumed that all of the <10 μm particles remained suspended indefinitely within 2 m of the ground, even though the vast majority would settle relatively rapidly under most conditions (Leavitt 2008). Nonetheless, this information was used to further heighten public fears. On top of this, a number of scientists and horticulturists came out against the program, claiming both that mating disruption would not effect eradication and that LBAM was not, on the basis of its potential for damage, a pest worth trying to eradicate (Carey and Harder 2013; Chen 2010). Environmentally, the sprays were claimed to have caused a large die-off of seabirds, a red tide algal bloom, disappearances of song birds, illness and death of pets, and bee kills (Upton 2008).

Lawsuits were filed to block the spraying. Local officials, including some mayors, joined the opposition to the treatments, and municipalities passed resolutions against the spraying (Lieber 2008). Before the end of 2008, the program had abandoned the idea of aerially applied mating disruption, which, along with rapid growth and spread of the LBAM population, effectively ended any realistic chance of eradication (Suckling et al. 2014). Development of the sterile insect technique for LBAM had started before the moth was detected in California, and was accelerated in 2008 as a possible alternative, but that effort was terminated in 2011 because there was no need for the technique following a realignment in the program's objectives.

A grand experiment ensues every time an organism is released into a novel environment, and the outcomes can be difficult to predict. For example, the emerald ash borer (*Agrilus planipennis* Fairmaire) is minimally a pest in its native range but has been functionally removing ash (*Fraxinus* spp.) from North American forests (Herms and McCullough 2014). In the case of LBAM, damage in California has not been as severe as feared based on New Zealand's early experience, apparently in large part due to effects of existing natural enemies of indigenous leafrollers (Bürgi and Mills 2013; Hogg et al. 2013). As of this writing, however, LBAM remains a market access problem for California agriculture, requiring monitoring, maintenance of quarantines, and approved treatments on regulated commodities that are scheduled for shipment outside of infested areas (USDA-APHIS-PPQ 2016c).

Although wide-scale eradication treatments ended in 2007, opponents of the program have persisted in criticism – articles questioning the choices made and subsequent rebuttals were published in American Entomologist in 2013 and 2014 (Carey and Harder 2013; Liebhold 2014). The last suit to block spraying wasn't settled until late 2015, over 8 years after the last spray was conducted and over 7 years after the program had decided that no future aerial applications would be made (Clark 2015). This suit unfortunately also blocked programmatic use of Isomate twist ties, which had been effective since the initiation of the program for eliminating small isolated populations. Mating disruption remains an acceptable alternative for growers, and efforts to improve methodology have continued (Suckling et al. 2012a, 2012b).

European Grapevine Moth The European grapevine moth (EGVM), *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae) is one of the most serious grape pests throughout its range (Bournier 1976). As the common name implies, the species is native to Europe and is a pest there, especially throughout more southern grape-growing areas. It has spread into Russia and through the Mediterranean area, and more recently has been found in Japan (early 1970's), Chile (2008), and California (2009) (Gilligan et al. 2011; Varela et al. 2010a). As EGVM go through multiple generations per year, the larvae develop on multiple grape tissues, including flowers and fruit among others (Ioriatti et al. 2011; Lucchi et al. 2011). EGVM will utilize a number of alternate host plants including *Daphne* (a suspected ancestral host), stone fruits, cane fruits, and flowering olives (Gutierrez et al. 2012; Thiéry and Moreau 2005). The species often has been referred to as polyphagous, although *Daphne* and *Vitus*, if available, will be used to the exclusion of other hosts under most conditions (Varela et al. 2010a).

A single-component sex attractant, (*Z*7,*E*9)-dodecadienyl acetate, was reported in the early 1970's (Roelofs et al. 1973). More recent studies have identified additional components that show activity in laboratory tests (El-Sayed et al. 1999; Witzgall et al. 2005), but the single component still is used for monitoring and control purposes. Mating disruption for EGVM has been researched extensively (reviewed by Ioriatti et al. 2011) and is used broadly as a control method in the EU (Cardé 2007). The vast majority of mating disruption treatments, for both research and control, have involved hand-applied dispensers, although machine-applied formulations have also been tested (Ioriatti et al. 2011; Teixeira et al. 2010).

European grapevine moth was identified in California in October 2009 after causing complete crop loss from two vineyards in Napa Valley (Gilligan et al. 2011). Delimitation trapping was initiated, and a Technical Working Group (TWG) was assembled, including members from USDA, universities, and four foreign countries (Chile, France, Germany, and Italy), as well as a viticulturist from the Napa area. In its early reports (February and May 2010), the TWG outlined strategies for delimiting the population as well as a statewide detection effort, and it recommended proceeding toward eradication, as that would not rule out other options as program goals. The TWG felt that eradication was in fact achievable as long as the population did not expand far beyond its current range (as it was understood at the time of the second report), the grape industry remained behind the program, and several available control methods remained available (USDA-APHIS-PPQ 2016b). The recommended strategies included area-wide treatments of grape production areas with insecticides (primarily growth regulators or organic alternatives, as appropriate) within specified distances of each "positive" trap (trap capturing one or more moths) for the first two larval generations per year. Mating disruption treatments also were to be applied to areas within 500 m of a positive trap for at least two full generations after the last capture (Fig. 2). Isonet-L twist-ties (Shin-Estu) were used because they were available and had proven efficacy against EGVM (Bagnoli et al. 2006; Ioriatti et al. 2011; Vassiliou 2009). Residential areas with backyard grapes were treated by stripping flowers and fruit and/or Btk applications. Regulatory measures were defined and quarantine boundaries were set up (Cooper et al. 2014; USDA-APHIS-PPQ 2016a).

Over 100,000 moths were caught in 2010. The vast majority were captured throughout much of Napa County, although the population had spilled over into two neighboring counties: there were sparse captures through a large portion of Sonoma County as well as a smaller section of Solano County that was adjacent to Napa (USDA-APHIS-PPQ 2016a). In 2010 and 2011, small, isolated pockets of EGVM were detected in grape-growing areas in seven additional counties in California, apparently from anthropogenic movement out of the Napa area (grape stakes were implicated in one case) (USDA-APHIS-PPQ 2016a).

The program went well from the start. The government agencies at federal, state, and county levels shared responsibility for trapping, purchase of mating disruption dispensers, and regulatory procedures and enforcement. County personnel also coordinated the insecticide treatments and, in the case of at least four counties (Napa, Sonoma, Mendocino, Fresno), hired or assigned people specifically to this task. The job was complex, as the individual growers were responsible for purchasing the insecticides and then applying them with proper timing. Fortunately, the grower groups and county government agencies remained firmly behind the program.

Numbers of moths in traps dropped from over 100,000 in 2010 to only 146 in 2011, 77 in 2012, and 40 in 2013. In 2012 and 2013, there were no captures outside of Napa County, and quarantined areas in the seven remote counties were subsequently deregulated. The one concern was that the 40 captures in 2013 were somewhat more scattered through Napa County (31 positive trap records) than the 77 caught in 2011 (19 trap records). However, in 2014, only one moth was caught, and that was in Sonoma County, outside of the regulated area. Per protocol, that moth did not trigger or extend any quarantines (USDA-APHIS-PPQ 2016a).

Based on a TWG recommendation, the program requires, in the Napa area, six full moth flights (generations) with no captures before deregulating and declaring eradication (USDA-APHIS-PPQ 2016b). In Napa County, that translates to 3 seasons, as a portion of the population diapauses after the 2nd generation each year (Cooper et al. 2014). In addition, for the last four of those six flights, trapping had to be at a high density (in grape production areas, 39 traps per km^2), and there could be no mating disruption treatments in the area, as that would reduce trap effectiveness. Mating disruption dispensers had been in place in 2014 around sites of 2013 captures. In 2015, there were no disruption treatments, high-density trapping was in place, and no EGVM were caught (USDA-APHIS-PPQ 2016a). If none are caught again in 2016, the remaining quarantine could be lifted by mid-August.

As this was an active eradication program, there were no test plots or other sources of data that could be used to quantify the relative contributions of insecticides and mating disruption on control of EGVM. However, comments from a number of program personnel to one of the authors [DRL] universally expressed the opinion that mating disruption had played an important role. In particular, in 2014, a further incremental reduction in captures had been the hope or perhaps expectation, especially after 2013's scattered captures throughout some areas of the Napa Valley where no moths had been caught the previous year. The sudden absence of moths in Napa County in 2014 was unexpected but occurred at a point

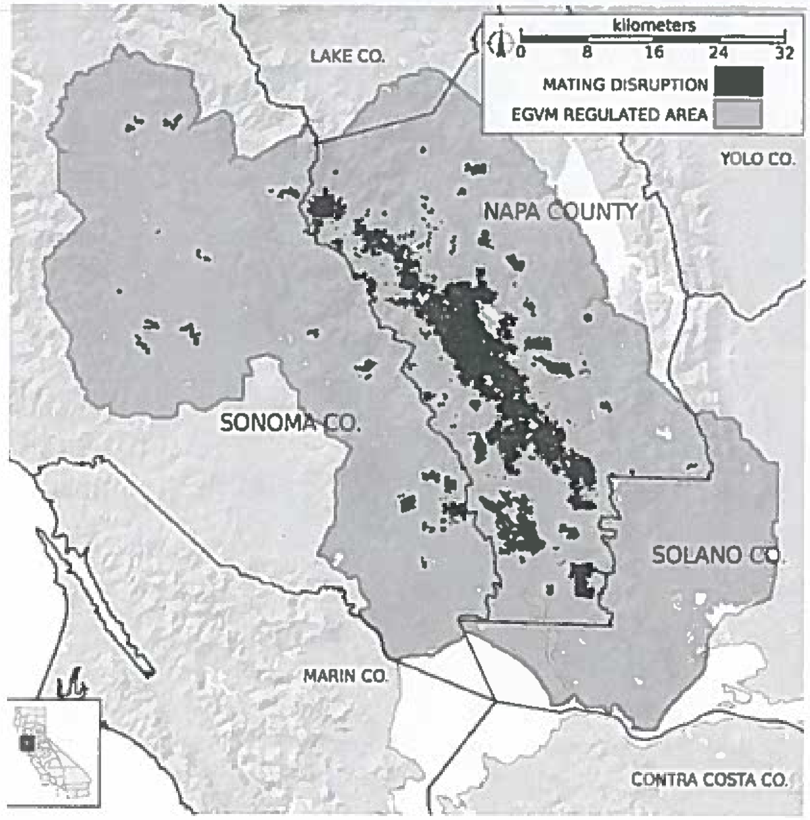

Fig. 2 Portions of Napa, Sonoma, and Solano Counties that were regulated for European grapevine moth at the height of the program, 2011–2012 (~3900 km^2). In Napa County, ~160 km^2 of commercial vineyards were treated with mating disruption during the program, with a concentration in Napa Valley (shown in black). In addition, 358 and 131 residential sites were treated in 2013 and 2014, respectively. In Sonoma County, 16 km^2 of grape acreage were treated

in the eradication program where mating disruption could theoretically have had maximal effect. In addition, the combination of ongoing insecticide treatments and mating disruption should in theory have synergistic effects (Liebhold et al. 2016; Suckling et al. 2012c). There were no apparent complaints of health or environmental concerns that arose due to the mating disruption treatments.

Lessons Learned and Conclusions

In general, mating disruption has proven to be a valuable tool in a number of large-scale programs targeting invasive pest Lepidopterans. As discussed above, the minimal human health and environmental safety of mating disruption, along with its species-specificity and compatibility with other tactics, such as chemical and biological control, can ease and simplify various aspects of regulatory programs. Certainly, with PBW and EGVM, pheromone treatment was a valuable tool in an integrated approach to eradication. Because mating disruption treatments in these two programs were confined almost exclusively to agricultural areas and often or, in the case of EGVM, only involved hand-applied materials, there was little opportunity for application of pheromone formulations to interact with the general public. Regarding the two programs where mating disruption treatments were applied aerially as a primary control over residential areas, the disparity between the California LBAM program and gypsy moth STS is difficult to reconcile. The degree of public outcry against the treatments in California took the LBAM program largely by surprise, although in initial discussions, at least one CDFA employee voiced the opinion privately that the program would fail due to public pressure if it relied on aerial applications. Enhanced outreach and education efforts may have helped. This could have included, for example, incorporation of new communication mechanisms (e.g., social media) along with more intensive monitoring of potential health and non-target effects – comparable to levels that would be appropriate for programs using more conventional toxic insecticides (Cooper et al. 2014; Zalom et al. 2013). We do not know, however, if such efforts would have made a difference in the LBAM program. Ironically, the lack of required testing associated with registration of pheromone-based control methods (EPA 2001) may have actually hurt the LBAM program as it reduced the amount of data available to refute claims that the materials may have been toxic or harmful to the environment. Cultural differences between California and the Midwest and South may have been involved, but it is difficult to believe that other factors were not at play as well.

Additional data on the use of mating disruption for eradication would be helpful in gaining acceptance of the strategy by skeptical members of the plant protection and scientific communities. To the degree that those skeptics gain a voice with the media (Chen 2010), it also could improve buy-in from the public. For example, data on eradication from controlled or semi-controlled field tests, or from demonstration trials, are needed to help counter arguments that mating disruption is not a proven eradication tool. Further modeling studies that address mating disruption for eradication of specific species also would be useful, not only in providing a theoretical basis for the strategy, but also for identifying parameter values for field tests and defining expectations of programs in terms of factors such as effects of population size and its relation to numbers of required generations to treat. Careful tracking and subsequent analysis of operational mating disruption programs also could provide data useful for subsequent efforts. Another reason for slow adoption of mating disruption for eradication has been the reduction in effectiveness of pheromone-baited traps, which typically are the most sensitive tool available for monitoring populations of target pests. With long-lasting formulations, partial suppression of catch can continue for at least a generation beyond the period of active treatment (Onufrieva et al. 2015). Declaring eradication with an acceptable level of confidence often requires highly sensitive trapping arrays applied across a specified number of pest generations (Lance 2014), which typically would not include generations exposed to mating disruption treatment. As such, applications must be suspended well before the expected termination of the program, and the choice to use mating disruption can in fact extend a program (USDA-APHIS-PPQ 2016b). Possible strategies for recovering at least partial performance of traps under disruption treatments include high-dose lures, ensuring that the complete pheromone blend is present in the lure, and use of kairomonal attractants, although the effectiveness of these strategies will vary among species (El-Sayed et al. 2011; Knight and Light 2005). Finally, our experience with LBAM highlights the need to go to the field with mating disruption formulations that are known to be effective. Specifically, additional data on performance of machine (including aerially) applied formulations, both generically and targeting individual high-risk pests, could improve the efficacy and cost-effectiveness of future programs.

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Guar gum CAS No 9000-30-0	MATERIAL SAFETY DATA SHEET SDS/MSDS

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifiers

Product name : **Guar gum**

CAS-No. : 9000-30-0

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses : Laboratory chemicals, Industrial & for professional use only.

1.3 Details of the supplier of the safety data sheet

Company : Central Drug House (P) Ltd
7/28 Vardaan House
New Delhi-10002
INDIA

Telephone : +91 11 49404040
Email : care@cdhfinechemical.com

1.4 Emergency telephone number

Emergency Phone # : +91 11 49404040 (9:00am - 6:00 pm) [Office hours]

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Not a hazardous substance or mixture according to Regulation (EC) No. 1272/2008.
This substance is not classified as dangerous according to Directive 67/548/EEC.

2.2 Label elements

The product does not need to be labelled in accordance with EC directives or respective national laws.

2.3 Other hazards

This substance/mixture contains no components considered to be either persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher.

SECTION 3: Composition/information on ingredients

3.1 Substances

Synonyms : Gum guar

CAS-No. : 9000-30-0
EC-No. : 232-536-8

No components need to be disclosed according to the applicable regulations.

SECTION 4: First aid measures

4.1 Description of first aid measures

If inhaled
If breathed in, move person into fresh air. If not breathing, give artificial respiration.

In case of skin contact
Wash off with soap and plenty of water.

In case of eye contact
Flush eyes with water as a precaution.

If swallowed
Never give anything by mouth to an unconscious person. Rinse mouth with water.

4.2 Most important symptoms and effects, both acute and delayed
The most important known symptoms and effects are described in the labelling (see section 2.2) and/or in section 11

4.3 Indication of any immediate medical attention and special treatment needed
No data available

SECTION 5: Firefighting measures

5.1 Extinguishing media

Suitable extinguishing media
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

5.2 Special hazards arising from the substance or mixture
Carbon oxides

5.3 Advice for firefighters
Wear self-contained breathing apparatus for firefighting if necessary.

5.4 Further information
No data available

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures
Avoid dust formation. Avoid breathing vapours, mist or gas.
For personal protection see section 8.

6.2 Environmental precautions
No special environmental precautions required.

6.3 Methods and materials for containment and cleaning up
Sweep up and shovel. Keep in suitable, closed containers for disposal.

6.4 Reference to other sections
For disposal see section 13.

SECTION 7: Handling and storage

7.1 Precautions for safe handling
Provide appropriate exhaust ventilation at places where dust is formed.
For precautions see section 2.2.

7.2 Conditions for safe storage, including any incompatibilities
Store in cool place. Keep container tightly closed in a dry and well-ventilated place.
Storage class (TRGS 510): Non Combustible Solids

7.3 Specific end use(s)
Apart from the uses mentioned in section 1.2 no other specific uses are stipulated

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Components with workplace control parameters

8.2 Exposure controls

Appropriate engineering controls
General industrial hygiene practice.

Personal protective equipment

Eye/face protection
Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU).

Skin protection
Handle with gloves. Gloves must be inspected prior to use. Use proper glove removal technique (without touching glove's outer surface) to avoid skin contact with this product. Dispose of contaminated gloves after use in accordance with applicable laws and good laboratory practices. Wash and dry hands.

Body Protection
Choose body protection in relation to its type, to the concentration and amount of dangerous substances, and to the specific work-place., The type of protective equipment must be selected according to the concentration and amount of the dangerous substance at the specific workplace.

Respiratory protection
Respiratory protection is not required. Where protection from nuisance levels of dusts are desired, use type N95 (US) or type P1 (EN 143) dust masks. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

Control of environmental exposure
No special environmental precautions required.

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

a) Appearance	Form: powder Colour: beige
b) Odour	No data available
c) Odour Threshold	No data available
d) pH	No data available
e) Melting point/freezing point	No data available
f) Initial boiling point and boiling range	No data available
g) Flash point	No data available
h) Evaporation rate	No data available
i) Flammability (solid, gas)	No data available
j) Upper/lower flammability or explosive limits	No data available
k) Vapour pressure	No data available
l) Vapour density	No data available

m) Relative density	No data available
n) Water solubility	No data available
o) Partition coefficient: n-octanol/water	No data available
p) Auto-ignition temperature	No data available
q) Decomposition temperature	No data available
r) Viscosity	No data available
s) Explosive properties	No data available
t) Oxidizing properties	No data available

9.2 Other safety information
No data available

SECTION 10: Stability and reactivity

10.1 Reactivity
No data available

10.2 Chemical stability
Stable under recommended storage conditions.

10.3 Possibility of hazardous reactions
No data available

10.4 Conditions to avoid
No data available

10.5 Incompatible materials
Strong oxidizing agents

10.6 Hazardous decomposition products
Other decomposition products - No data available
In the event of fire: see section 5

SECTION 11: Toxicological information

11.1 Information on toxicological effects

Acute toxicity
LD50 Oral - Rat - 6.770 mg/kg

Skin corrosion/irritation
No data available

Serious eye damage/eye irritation
No data available

Respiratory or skin sensitisation
No data available

Germ cell mutagenicity
No data available

Carcinogenicity

IARC: No component of this product present at levels greater than or equal to 0.1% is identified as probable, possible or confirmed human carcinogen by IARC.

Reproductive toxicity

No data available

Specific target organ toxicity - single exposure
No data available

Specific target organ toxicity - repeated exposure
No data available

Aspiration hazard
No data available

Additional Information
RTECS: Not available

To the best of our knowledge, the chemical, physical, and toxicological properties have not been thoroughly investigated.

SECTION 12: Ecological information

12.1 Toxicity

Toxicity to fish	LC50 - Oncorhynchus mykiss (rainbow trout) - 218 mg/l - 96 h

12.2 Persistence and degradability
No data available

12.3 Bioaccumulative potential
No data available

12.4 Mobility in soil
No data available

12.5 Results of PBT and vPvB assessment
This substance/mixture contains no components considered to be either persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher.

12.6 Other adverse effects
No data available

SECTION 13: Disposal considerations

13.1 Waste treatment methods

Product
Offer surplus and non-recyclable solutions to a licensed disposal company.

Contaminated packaging
Dispose of as unused product.

SECTION 14: Transport information

14.1 UN number

ADR/RID: -	IMDG: -	IATA: -

14.2 UN proper shipping name

ADR/RID:	Not dangerous goods
IMDG:	Not dangerous goods
IATA:	Not dangerous goods

14.3 Transport hazard class(es)

ADR/RID: -	IMDG: -	IATA: -

14.4 Packaging group

ADR/RID: -	IMDG: -	IATA: -

14.5 Environmental hazards

ADR/RID: no	IMDG Marine pollutant: no	IATA: no

14.6 Special precautions for user
No data available

SECTION 15: Regulatory information

This safety datasheet complies with the requirements of Regulation (EC) No. 1907/2006.

15.1 Safety, health and environmental regulations/legislation specific for the substance or mixture

No data available

15.2 Chemical Safety Assessment

For this product a chemical safety assessment was not carried out

SECTION 16: Other information

Further information

The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Central Drug House (P) Ltd and its Affiliates shall not be held liable for any damage resulting from handling or from contact with the above product. See www.cdhfinechemical.com for additional terms and conditions of sale.

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REVIEW

Guar gum: processing, properties and food applications—A Review

Deepak Mudgil · Sheweta Barak · Bhupendar Singh Khatkar

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Abstract Guar gum is a novel agrochemical processed from endosperm of cluster bean. It is largely used in the form of guar gum powder as an additive in food, pharmaceuticals, paper, textile, explosive, oil well drilling and cosmetics industry. Industrial applications of guar gum are possible because of its ability to form hydrogen bonding with water molecule. Thus, it is chiefly used as thickener and stabilizer. It is also beneficial in the control of many health problems like diabetes, bowel movements, heart disease and colon cancer. This article focuses on production, processing, composition, properties, food applications and health benefits of guar gum.

Keywords Cholesterol · Cluster bean · Dietary fiber · Guar gum · Hydration rate · Viscosity

Introduction

Guar gum is derived from the seeds of the drought tolerant plant *Cyamopsis tetragonoloba*, a member of Leguminosae family (Whistler and Hymowitz 1979; Kay 1979; Prem et al. 2005). The common names used in the scientific literature for the bean, guar gum flour and the galactomannan fraction are Indian cluster bean, guar and guaran, respectively. There is lack of general consensus with regard to the origins of this plant (Whistler and Hymowitz 1979), although the concept of transdomestication was originally proposed by Hymowitz (1972). This hypothesis explained how the domesticated guar plant, *C. tetragonoloba*, developed from the drought-tolerant wild Africa species *C. senegalensis*. The latter species was originally taken from Africa to South Asian subcontinent by Arab traders as fodder for horses probably some time between the 9th and 13th centuries A.D. The domesticated species is normally associated with India and Pakistan, where the plant has been grown for centuries as food for both human and animals (Whistler and Hymowitz 1979). Guar gum industry developed in the 1940s and 1950s in United States (BeMiller 2009). Guar was brought into the United States before World War I primarily as a green manure but was not used in industrial applications until 1943 and probably it was the main reason why it has been studied to a limited scale. At that time, the supply of locust bean gum, which was widely used in the paper and textile industries and imported from Europe and North Africa had declined and was difficult to get. Therefore, the Institute of Paper Chemistry, Appleton, Wisconsin and United States Department of Agriculture made an effort to find a domestic plant that could provide a substitute for locust bean gum. This search led to the reexamination of guar gum and it was found to be the best solution of the problem. The commercial development was made at the University of Arizona during World War II. At the close of the war the gum was examined by Whistler (1948) at Purdue. He worked on the molecular structure and, in examining the properties of the pure polysaccharide, guaran, visualized its wide industrial potential and recommended development of the guar plant as a domestic crop for industry (Whistler 1948; Whistler and Hymowitz 1979). Studies had revealed that the gum is a valuable paper maker's adjunct in obtaining temporary wet strength in sheets, such as paper toweling and this gum facilitates hydration during the beating of various pulps. The services of the Soil Conservation Commission of the U. S. Department of Agriculture were enlisted and as a result,

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numerous seeds were investigated for their potentialities. The most satisfactory results were found from those of guar or Cyamopsis tetragonolobus, an annual drought-resistant leguminous plant, three to six feet tall, which has been cultivated in certain sections of India for centuries as fodder for cattle and horses.

Guar gum resembles locust bean gum in being composed essentially of the complex carbohydrate polymer of galactose and mannose, but with different proportions of these two sugars. It is reported that guar flour is of value as a beater additive for improving the strength of certain grades of paper. It has also been reported that guar possesses properties which might be useful in warp sizing, printing pastes, and in certain finishing operations. In order to obtain the gum it is necessary to separate the gum-containing endosperm of the seed from the outer and largely fibrous portions.

Consumption of guar gum rapidly increased but it was the development of anionic and cationic guar gum derivatives and their use in oil and gas well stimulation that gave guar gum its present commercial importance. In textile and carpet printing, guar gum thickens the dye solutions which allow more sharply printed patterns to be produced. Guar gum has been used in explosives for over 25 years as an additive to dynamite for water blocking. In recent years, it has become the primary gelling agent in water based slurry explosives. The production of paper is enhanced by an addition of small amounts of guar gum to the pulp. It serves as a fiber deflocculent and dry-strength additive.

Guar seed endosperm is a source of water soluble gum which is used as stabilizer, emulsifier and thickener in various food products and contributes to soluble dietary fiber (SDF) portion of seed total dietary fiber (TDF). TDF and SDF, respectively, made up 52–58% and 26–32% of seed dry weight (Kays et al. 2006). As a food additive, it emulsifies, binds water, prevents ice crystals in frozen products, moisturizes, thickens, stabilizes and suspends many liquid–solid systems. It is used in ice cream, sauces, cake mixes, cheese spreads, fruit drinks and dressings usually in amount of <1% of the food weight (Whistler and Hymowitz 1979; Parija et al. 2001).

Production

Guar gum is a gel-forming galactomannan obtained by grinding the endosperm portion of *Cyamopsis tetragonolobus*, a leguminous plant grown for centuries mainly in India and Pakistan where it is a most important crop that has long been used as food for humans and animals (Chandirami 1957). The guar plant is essentially a sun-loving plant, tolerant of high environmental temperatures but very susceptible to frost (Whistler and Hymowitz 1979; Kay 1979). For maximum growth the plant requires a soil temperature of 25–30 °C and ideally, a dry climate with sparse but regular rainfall. Guar plant requires rain for optimum growth before planting and again to induce maturation of seeds (Anderson, 1949). Excess of moisture during early phase of growth and after maturation of seeds results in lower quality guar beans (Heyne & Whistler 1948; Venkateswarlu et al. 1982). The rain pattern of the monsoons in the northern parts of India and Pakistan generally provides ideal growing conditions for guar. Almost 90% of world's guar is grown in India and Pakistan. Unique requirement of right amount of rain at a particular time of growth and maturation makes this crop largely dependent on annual rainfall pattern and causes occasional wide swings in guar supply and prices. Guar is also cultivated in the southern hemisphere in semi-arid zones in Brazil, Australia, South Africa and Southern part of the USA like Texas or Arizona. The total production of guar seed in these countries is estimated at 15,000 MT annually. The agro-climatic conditions in Australia are also quite conducive to the cultivation of guar. Efforts have been made to promote cultivation of guar in Australia by the Department of Agriculture and Rural Industrial Development Agency. Similarly, it is reported that countries like China and Thailand are also trying to grow guar. Therefore, in future guar may not remain monopoly of India and Pakistan.

India accounts for 80% of the total guar produced in the world and 70% of it is cultivated in Rajasthan. India is the world leader for production of guar, which is grown in the northwestern parts of country encompassing states of Rajasthan, Gujrat, Haryana and Punjab. During 1970s guar was also grown regularly in the State of Uttar Pradesh (U.P.), Madhya Pradesh (M.P.) and Orissa. As the processing facilities have been closed down in U.P. and M.P., the cultivation in these states is negligible now. In Orissa too guar is not cultivated any more. The annual production of guar during last 3 years ranged from 11, 00,000 to 12, 87,000 MT.

In Pakistan, before 90s, about 80% of the guar was grown under irrigated conditions therefore per hectare yield was higher. During that period guar was grown in Punjab, Multan, Muzaffargarh, Mianwali and Sargoda. The other areas include Bahawalpur, Banawalnagar and Sind Province. The annual production of guar during this period ranged between 180,000 and 250,000 MT annually. List of Indian guar products importing countries is as given in Table 1.

Processing

Guar gum processing varies from plant to plant. The general outline of the manufacturing process of guar gum is shown in Fig. 1. When guar seeds are removed from their pods these are spherical in shape, brownish in color, smaller than pea seeds in size.

Table 1 Country wise export data of Indian guar gum from 2008 to 2010 (APEDA 2011)

Country	Percent Export		
	2007–08	2008–09	2009–10
United States	38.7	37.6	32.9
China	16.2	15.2	11.6
Germany	8.5	8.7	9.4
South Africa	4.2	1.7	1.4
Malaysia	2.9	3.8	3.8
Italy	2.3	2.3	3.1
Netherland	2.1	1.5	1.5
Australia	1.8	2.5	1.8
Russia	1.8	2.6	2.8
Vietnam	1.4	4.1	3.7
Others	20.1	30.0	28.0

The gum is commercially extracted from seeds essentially by a mechanical process of roasting, differential attrition, sieving and polishing. The seeds are broken and the germ is separated from the endosperm. Two halves of the endosperm are obtained from each seed and are known as undehusked guar split. When the fine layer of fibrous material, which forms the husk, is removed and separated from the endosperm halves by polishing, refined guar splits are obtained. The hull

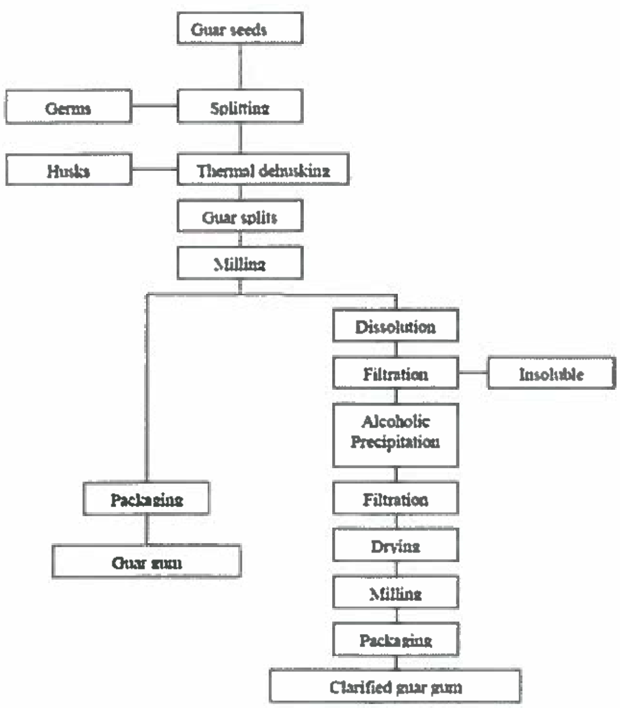

Fig. 1 Flow diagram for industrial manufacturing of guar gum

(husk) and germ portion of guar seed are termed as guar meal which is a major byproduct of guar gum powder processing and is utilized as cattle feed. The refined guar splits are then treated and finished into powders (known as guar gum) by a variety of routes and processing techniques depending upon the end product desired. The pre hydrated guar splits are crushed in flacker mill and then uniformly moved to ultra fine grinder, which grinds the splits without producing too much heat. The grinded material is dried and passed through screens for grading of the material according to the particle size. Various grades are available depending upon color, mesh size, viscosity potential and rate of hydration (Chudzikowski 1971). In industrial processing of guar gum extrusion is also included before hydration and flaking. After these steps grinding and drying are done. Inclusion of extrusion gives guar gum powder with improved hydration rate (Chowdhary 2002). The byproducts of guar gum industry are Churi and Korma which are utilized for cattle feed.

Non-food applications

Demand of guar gum has increased during last few decades due to the development of different derivatives of guar gum like anionic and cationic derivatives. Present commercial importance of guar gum is because of its use in oil and gas well stimulation specifically hydraulic fracturing in which high pressure is used to crack rock. Guar gum makes the fracturing fluid thicker so that it can carry sand into fractured rock. This fracture remains open due to presence of sand which creates a path for gas or oil to flow to well bore. Guar derivatives for use in fracturing fluids are hydroxypropyl guar (HPG) and carboxymethyl hydroxypropyl guar (CMHPG). In textile and carpet printing, guar gum thickens the dye solutions which allow more sharply printed patterns to be produced. Guar gum has been used in explosives for over 25 years as an additive to dynamite for water blocking. In recent years, it has become the primary gelling agent in water based slurry explosives. Water blocking, swelling and gelling property of guar gum make it enable to use as an additive in explosive industry. Explosive property is maintained by mixing of ammonium nitrate, nitroglycerine and oil explosives with guar gum even in wet conditions. The production of paper is enhanced by an addition of small amounts of guar gum to the pulp. It serves as a fiber deflocculent and dry-strength additive. It provides denser surface to the paper used in printing. Research investigation shows that high viscosity guar gum derivatives can be obtained by treatment of guar gum with complexing agents like organic titanates, chromium salts and aluminum salts. These agents react with guar gum to form complexes with high viscosity gel.

Composition and structure

The guar kernel is composed of several layers, namely the outer husk (16–18%), the germ (43–46%) and the endosperm (34–40%). The germ portion of its seed is predominantly protein and the endosperm predominantly galactomannan. Guar gum mainly consists of the high molecular weight polysaccharides of galactomannans which are linear chain of (1→4)-linked β-D-mannopyranosyl units with (1→6)-linked α-D-galactopyranosyl residues as side chains as shown in Fig. 2. These galactose and mannose groups constitute the galactomannan portion of seed endosperm. General composition of guar gum is given in Table 2. It was first believed that the sidegroups were substituted at regular intervals along the mannan backbone (Whistler and Hymowitz 1979). However, experiment using enzyme degradation of guar (McCleary 1979), spectroscopic methods (Grasdalen and Painter, 1980) and computer simulation (McCleary et al. 1985), indicate more random distribution of galactose side groups as given in Fig. 3.

One such model proposes a guar galactomannan in which the galactosyl units are randomly arranged mainly in pairs and triplets (Hoffman and Svensson 1978). The ratio of mannose to galactose units has historically been reported as 2:1 (Garti and Leser 2001). Various research studies support ratios in the range of 1.6:1 to 1.8:1 (Grasdalen and Painter 1980; McCleary et al. 1985; Hoffman and Svensson 1978; Barth and Smith 1981; Vijayendran and Bone 1984; McCleary 1981; Mathur and Mathur 2005). Current data also suggest that galactomannans from different guar varieties have the same galactose/mannose arrangement (McCleary et al. 1985). The greater branching of guar is believed to be responsible for its easier hydration properties as well as its greater hydrogen bonding activity (Whistler 1954). It is also reported that aggregates are prominent in guar systems and may have important role in viscoelastic behavior of solution, depending on how they are interlinked (Gittings et al. 2000)

Guar is a polysaccharide with one of the highest molecular weights of all naturally occurring water soluble polymers. The viscosifying effect of commercial guar gum preparations can vary enormously depending on the molecular weight of the galactomannan. Early publications reported that average molecular weight of guar gum vary enormously, depending on what method is used, but these are typically in the range of 0.25–5.0 million.

Absolute methods have also been used to determine molecular weight, including light scattering techniques, which are also useful for providing structural information on the polysaccharide (Robinson et al. 1982; Burchard 1994; Ross-Murphy et al. 1998). One relatively simple and reliable way of estimating molecular weight is to use intrinsic viscosity measurements, calibrated by light scattering or some other absolute method using the Mark-Houwink equation. But more recent results obtained with size exclusion chromatography and low angle laser light scattering show the average molecular weight in the range of 10^6 to 2×10^6 (Barth and Smith 1981; Vijayendran and Bone 1984)

Physico-chemical properties

The biological properties of guar galactomannan and other such polysaccharides are dependent on their behavior in an aqueous medium. Guar gum swells and or dissolves in polar solvent on dispersion and form strong hydrogen bonds. In nonpolar solvents it forms only weak hydrogen bonds. The rate of guar gum dissolution and viscosity development generally increases with decreasing particle size, decreasing pH and increasing temperature. Hydration rates are reduced in the presence of dissolved salts and other water-binding agents such as sucrose (Bemiller and Whistler 1993).

Rheology

Rheology is the study of flow and deformation of material when external force is applied. Guar gum in aqueous solutions shows pseudoplastic or shear-thinning behavior

Fig. 2 Structure of guar gum molecule

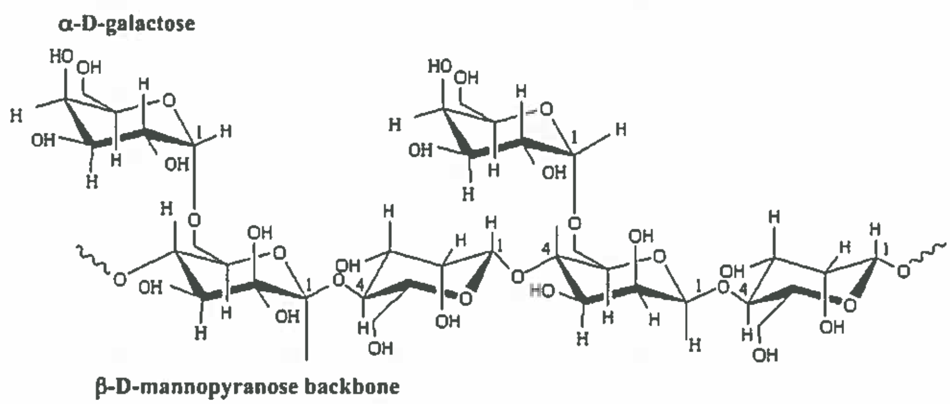

Table 2 General composition of guar gum (Chudzikowski 1971)

Constituent	Percentage
Galactomannan	75–85
Moisture	8.0–14
Protein (N x 6.25)	5.0–6.0
Fiber	2.0–3.0
Ash	0.5–1.0

which means reduction in viscosity with increasing shear rate as shown by many high molecular weight polymers. This shear-thinning behavior of guar gum aqueous solution increases with polymer concentration and molecular weight. Guar gum aqueous solutions also do not show yield stress properties (Whistler and Hymowitz 1979). Aqueous solutions of guar gum at 1% concentration show a typical behavior of macromolecular biopolymer with dominating loss modulus (G″) over storage modulus (G′) in lower frequency range. However, in high frequency range storage modulus dominates the loss modulus (Shobha and Tharanathan 2009). With time guar gum aqueous solutions showed a decrease in storage modulus (G′) and loss modulus (G″) (Chenlo et al. 2010).

Viscosity

The most significant characteristic of guar gum is its ability to hydrate rapidly in cold water systems to give highly viscous solutions. Guar gum forms a viscous colloidal dispersion when completely hydrated which is a thixotropic rheological system. Dilute solution of less than 1% concentration of guar gum are less thixotropic than solutions of concentration of 1% or higher (Glicksman 1969). As like the other gums, viscosity of guar gum is dependent on time, temperature, concentration, pH, ionic strength and also on type of agitation. Schlakman and Bartilucci (1957) examined thirteen different

Fig. 3 Sequence of galactose and mannose in guar

commercial samples, and found great variation in the viscosity property, particle size and rate of hydration. A 1% aqueous dispersion of good quality guar gum may show a high viscosity value of 10000 cP (Parija et al. 2001).

Hydration rate

Rate of hydration of guar gum varies. Hydration of about 2 h is required in practical applications in order to reach maximum viscosity. Hydration rate largely depend on particle size of guar gum powder. Hence, for quick initial viscosity, very fine mesh guar gums are available (Glicksman 1969). However, a considerable time interval is still desired for maximum hydration and viscosity to be achieved.

Hydrogen bonding activity

Hydrogen bonding activity of guar gum is due to the presence of hydroxyl group in guar gum molecule. Guar gum shows hydrogen bonding with cellulosic material and hydrated minerals. With slight addition of guar gum, there is alteration in electrokinetic properties of any system markedly (Glicksman 1969). Substitution of hydroxyl groups in guar gum with hydroxypropyl causes steric hindrance that decreases the stability of hydrogen bonds (Cheng and Prud'homme 2002).

Factors affecting viscosity and hydration rate

Viscosity and hydration rate of guar gum does not remain constant but changes with conditions like temperature, pH, solute, concentration, etc.

Temperature

Temperature is the most significant factor that affects the rate of hydration and maximum viscosity. Guar solutions reach maximum viscosity much faster when prepared at higher temperatures than those at lower temperatures. But the prolonged heat is also considered to have degradative effect. In most of the cases, guar gum solutions prepared by heating have a lower final viscosity than the same solutions prepared with cold water and allowed to hydrate slowly. Temperature range of 25–40 °C is desirable for maximum viscosities of guar gum dispersion. The viscosity of 0.5% (w/w) guar solution at 25 °C is significantly higher than that of 37 °C (Srichamroen 2007).

Concentration

Guar gum solution shows very high viscosity even at very low concentration. In most of the food applications it is recommended at below 1% concentration. Guar gum solution viscosities increase proportionally with increases in guar gum concentration (Morris et al. 1981; Robinson et al. 1982). This is due to the interaction of galactose side chain of guar molecule with water molecule. Increase in concentration of guar gum enhances the inter-molecular chain interaction or entanglement which leads to increase in viscosity (Zhang et al. 2005).On doubling the concentration guar gum shows tenfold increase in viscosity (Carlson et al. 1962). Upto 0.5% concentration, guar gum solutions behave as Newtonian system whereas above this concentration level guar solutions behave as non-Newtonian and thixotropic systems. It is also reported that viscosities of different concentration of guar gum at constant temperature reduces with increase in shear rate (Srichamroen 2007).

pH

Guar gum solutions are stable over a wide pH range of about 1.0–10.5. This is due to its non-ionic and uncharged behaviour. Final viscosity of guar gum is not affected by the pH, but the hydration rate shows variation with any change in pH. Fastest hydration is achieved at pH 8–9, however slowest hydration rate occurs at pH above 10 and below 4 (Carlson et al. 1962).

Sugar

In guar-sugar solution, sugar competes with guar gum molecule for the water available in the solution, hence presence of sugar in guar gum solution causes delay in hydration of guar gum molecules. The viscosity of guar-sugar solution decreases gradually and is inversely proportional to the sugar concentration (Carlson and Ziegenfuss 1965). Sweeteners like aspartame, acesulfame-k, cyclamate and neotame do not affect intrinsic viscosity of guar gum solutions significantly (Samavati et al. 2008).

Salt

Salt is most widely used ingredient in foods other than water, its effect on guar gum has been extensively studied (Carlson et al. 1962). Guar gum solutions in brine behave same as in water. Hydration rate is not influenced by salt; however, the presence of sodium chloride slightly increases the final viscosity of fully hydrated guar gum. Physiological buffer i.e. Krebs bicarbonate decreases the viscosity of 0.25% guar gum solution as compared to gaur gum in water alone (Srichamroen 2007). Salts restrict the hydration of guar gum solution (Doyle et al. 2006). Srichamroen demonstrated that viscosity of 0.5% guar gum solution increases with added salts. Presence of salts can help the intermolecular interactions due to change in the charge density and conformation of gum (Gittings et al. 2001).

Food applications

In food industry, guar gum is used as a novel food additive in various food products for food stabilization and as fiber source (Morris 2010). It is liked by both manufacturer and consumer because it is economical as well as natural additive. It is used in variety of foods as an additive because it changes the behaviour of water present as a common component in various foods. Some of the most common food applications of guar gum are shown in Table 3. Permissible use levels and limitations in various products are covered under Title 21 CFR 184.1339, affirming guar's "generally recognized as safe" (GRAS) status.

Beverages

Guar gum is used in beverages for thickening and viscosity control because of its several inherent properties. The important property of guar gum is its resistance to breakdown

Table 3 Food applications of guar gum

Food	Dose level	Function	Reference
Chapati	0.75%	Softness	Ghodke 2009
Bread	0.5%	Softness, loaf volume	Keskin et al. 2007; Ribotta et al. 2001
Fried Products	0.5–1.0%	Oil uptake reduction	Sakhale et al. 2011
Yoghurt	2.0%	Texture improver	Brennan and Tudorica 2008
Cake	0.15%	Fat replacer, Firmness	Zambrano et al. 2004
Sausage	0.13–0.32%	Softness	Andres et al. 2006
Pasta	1.5%	Texture improver	Raina et al. 2005
Ice cream	0.5%	Smaller ice crystals	Sutton and Wilcox 1998
Baked goods	1.0%	Dough improver	Kohajdova and Karovicova 2008
Tomato Ketchup	0.5–1.0%	Consistency improver, Serum loss reduction	Gujral et al. 2002 Koocheki et al. 2009

under low pH conditions present in beverages. Guar gum is soluble in cold water which makes it easy to use in beverage processing plants. It improves the shelf life of beverages.

Processed cheeses

In cheese product, syneresis or weeping is a problem of serious concern. Guar gum prevents syneresis or weeping by water phase management and thus also improves the texture and body of the product (Klis 1966). In cheese products it is allowed upto 3% of the total weight. Guar gum in the soft cheeses enhances the yield of curd solids and gives a softer curve with separated whey. Low-fat cheese can be produced with addition of guar gum (at concentration 0.0025–0.01% w/v) without changing the rheology and texture compared with full-fat cheese.

Dairy products

Main purpose of using guar gum in frozen products is stabilization. Guar gum has important role in ice cream stabilization because of its water binding properties. Its use in high temperature short time (HTST) processes is very favorable because such processes require hydrocolloids that can fully hydrate in a short processing time. According to McKiernan (1957) locust bean gum has all the properties of an ideal gum but it hydrates slowly which is not favorable in HTST process. Julien (1953) obtained satisfactory results with guar as stabilizer in continuous ice cream processing. Guar gum should be used in ice cream mix at a concentration level of 0.3% (Goldstein & Alter 1959a, b). It was also used in combination with carrageenan in a mixed guar-carrageenan system developed for HTST process. Like locust bean gum its performance can be improved when used in combination with other stabilizers (Weinstein 1958). Guar gum in ice cream improves the body, texture, chewiness and heat shock resistance. Partially hydrolyzed guar gum (at 2–6% concentration level) decreases syneresis and improves the textural and rheological properties of low-fat yoghurt comparable with full-fat yoghurt (Brennan and Tudorica 2008).

Processed meat products

Guar gum has strong water holding capacity in both hot and cold water. Hence, it is very effectively used as a binder and lubricant in the manufacturing of sausage products and stuffed meat products. It performs specific functions in processed meat products like syneresis control, prevention of fat migration during storage, viscosity control of liquid phase during processing and cooling and control of accumulation of the water in the can during storage. Guar gum also enhances the creaming stability and control rheology of emulsion prepared by egg yolk (Ercelebi and Ibanoglu 2010)

Bakery products

Addition of guar gum in cake and biscuit dough improves the machinability of the dough that is easily removed from the mold and can be easily sliced without crumbling. At 1% addition of in batter of doughnuts, it gives desirable binding and film-forming properties that decreases the penetration of fats and oils. Guar gum in combination with starch is found to be effective in prevention of dehydration, shrinking and cracking of frozen-pie fillings (Werbin 1950). In wheat bread dough, addition of guar gum results in significant increase in loaf volume on baking (Cawley 1964). Guar gum along with xanthan gum retard staling in gluten-free rice cakes by decreasing the weight loss and retrogradation enthalpy (Sumnu et al. 2010). Similarly, guar gum also retards staling in chapati at room temperature as well as refrigerated temperature by controlling retrogradation of starch (Shaikh et al. 2008).

Salad dressings and sauces

Its cold water dispersibility and compatibility with high acidic emulsions enable it to use as thickener in salad dressing at about 0.2–0.8% of total weight. In salad dressings, it acts as an emulsion stabilizer by enhancing the viscosity of water phase and hence decreasing the separation rate of the water and oil phase (Goldstein and Alter 1959a, b). Guar gum has been found useful as a thickener in place of tragacanth in pickle and relish sauces (Burrell 1958). Guar gum enhances the consistency of tomato ketchup more prominently than other hydrocolloids like carboxy methyl cellulose, Sodium alginate, gum acacia and pectin. On addition of guar gum serum loss and flow values of tomato ketchup decreases which makes it a novel thickener for tomato ketchup (Gujral et al. 2002).

Health benefits

Various studies have been conducted on animals to test for both harmful and beneficial effect of guar gum. Guar is completely degraded in the large intestine by Clostridium butyricum (Hartemink et al. 1999). Harmful effects are observed only when the guar gum is given to the animals at a high concentration of about 10–15% on weight basis. This high concentration will reduce growth of animal due to decreased feed intake and impaired digestion. It is considered that the high viscosity of the intestinal tract contents, resulting from intake of guar gum at higher concentration, is the major cause of the negative effects.

Hence, guar gum can only be used for its beneficial effects at lower concentration of about 0.5–1.0%. Above this concentration it will show negative effects of higher viscosity, decreased protein efficacy and lipid utilization. High viscosity of guar gum when used at a higher concentration, above 1.0% will not only interfere with nutritional properties of the food but also with the physicochemical and sensory properties of the food product which is not accepted by the consumer. Partial hydrolysis of guar gum (PHGG) reduces the chain length and molecular weight of the polymer and ultimately the lower viscosity makes it a novel soluble fiber that resembles in basic chemical structure with native guar gum and has various applications in clinical nutrition associated with ingestion of dietary fiber. It solves all the problems of high viscosity of guar gum. With hydrolyzed guar gum it is possible to increase the dietary fiber content of various food products like beverages without disturbing the nutritional and sensory properties of the food products. PHGG supplementation to the diet also reduces the laxative requirement, incidence of diarrhea and symptoms of irritable bowel syndrome (Greenberg and Sellman 1998; Slavin and Greenberg 2003). For treatment of irritable bowel syndrome water soluble non-gelling fibers are preferred. Due to its water solubility and non-gelling behavior, partially hydrolyzed guar gum decreased the symptoms in both forms of irritable bowel syndrome i.e. constipation predominant and diarrhea predominant (Giannini et al. 2006).

In vitro study shows that presence of guar gum significantly decreases the digestion of starch. It acts as a barrier between starch and starch hydrolyzing enzymes (Dartois et al. 2010).

Guar gum shows cholesterol and glucose lowering effects because of its gel forming properties. It also helps in weight loss and obesity prevention. Due to gel forming capacity of guar gum soluble fiber, an increased satiation is achieved because of slow gastric emptying. Diet supplemented with guar gum decreased the appetite, hunger and desire for eating (Butt et al. 2007). Mechanism behind cholesterol lowering by guar gum is due to increase in excretion of bile acids in faecus and decrease in enterohepatic bile acid which may enhances the production of bile acids from cholesterol and thus hepatic free cholesterol concentration is reduced (Rideout et al. 2008). Hypotriacylglycerolaemic effects are due to decrease in absorption of dietary lipids and reduced activity of fatty acid synthase in liver (Yamamoto 2001). Toxicity study on partially hydrolyzed guar gum has revealed that it is not mutagenic upto dose level of 2500 mg/day (Takahashi et al., 1994). Adequate intake of guar gum as dietary fiber helps in the maintenance of bowel regularity, significant reductions in total and LDL-cholesterol, control of diabetes, enhancement of mineral absorption and prevention of digestive problems like constipation (Yoon et al. 2008).

Conclusion

Guar gum is an important agrochemical derived from the seed endosperm of guar plant i.e. Cymopsis tetragonolobus which is cultivated in India and Pakistan from ancient times. Guar gum is a useful material to investigate. It has a strong hydrogen bond forming tendency in water which makes it a novel thickener and stabilizer. Aqueous solutions of guar gum are very viscous in nature. Because of these properties it has wide applications in the industries like food, pharmaceutical, textile, oil, paint, paper, explosive and cosmetics. Another reason for its popularity in the industry is its low cost. Its economical nature makes it popular in gums and stabilizers industry. In food industry, it has wide applications in ice cream, sauce, beverages, bakery and meat industry. It is also used in food products for supplementation as dietary fiber. Its consumption reduces the risk of heart diseases by reducing the cholesterol level in body, control diabetes and maintains the bowel movement in human beings.

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SAFETY DATA SHEET

Revision Date 23-May-2015
Version 2

1. Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier

Product name	Aurora Pink® Pigment
Product code	AX-11-5

1.2 Relevant identified uses of the substance or mixture and uses advised against

Recommended Use	Pigment
Restrictions on use	No information available

1.3 Details of the supplier of the safety data sheet

Supplier
DayGlo Color Corp.
4515 St. Clair Avenue
Cleveland, OH 44103
(216) 391-7070
+1 216-391-7070 (outside the US) This telephone number is available during office hours only.

E-mail Address ehs@dayglo.com

1.4 Emergency telephone number

Emergency telephone number
Chemtrec: +1 703-527-3887 ex-USA
Chemtrec: 1-800-424-9300 USA

2. Hazards identification

2.1 Classification of the substance or mixture

GHS Classification in accordance with 29 CFR 1910.1200

2.2 Label elements

This product is not classified.

2.3 Other Hazards Hazards not otherwise classified (HNOC)
Not Applicable

2.4 Other information
Not Applicable

3. Composition/Information on Ingredients

Substance

Chemical Name	CAS-No	Weight %
C.I. Basic Violet 11:1, Tetrachlorozincate	73398-89-7	1 - 5

* The exact percentage (concentration) of composition has been withheld as a trade secret.

4. First aid measures

4.1 Description of first-aid measures

General advice No information available.

Eye contact Immediately flush with plenty of water. After initial flushing, remove any contact lenses and continue flushing for at least 15 minutes. Keep eye wide open while rinsing. If symptoms persist, call a physician.

Skin contact Immediate medical attention is not required. Wash off with soap and water.

Inhalation Immediate medical attention is not required. Move to fresh air.

Ingestion Do NOT induce vomiting. Drink plenty of water. Consult a physician.

4.2 Most important symptoms and effects, both acute and delayed

Symptoms See Section 2.2, Label Elements and/or Section 11, Toxicological effects.

4.3 Recommendations for immediate medical care and/or special treatment

Notes to physician Treat symptomatically.

5. Fire-Fighting Measures

5.1 Extinguishing media

Suitable extinguishing media
Use extinguishing measures that are appropriate to local circumstances and the surrounding environment.

Unsuitable Extinguishing Media None.

5.2 Specific hazards arising from the substance or mixture

Special Hazard
None known based on information supplied

Hazardous Combustion Products Carbon oxides. Nitrogen oxides (NOx). Oxides of sulfur.

Explosion Data
Sensitivity to Mechanical Impact None.
Sensitivity to Static Discharge Fine dust dispersed in air, in sufficient concentrations, and in the presence of an ignition source is a potential dust explosion hazard.

5.3 Advice for firefighters

As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

6. Accidental Release Measures

6.1 Personal precautions, protective equipment and emergency procedures

Ensure adequate ventilation, especially in confined areas. Use personal protective equipment.

6.2 Environmental precautions

Dust deposits should not be allowed to accumulate on surfaces as these may form an explosive mixture if they are released into the atmosphere in sufficient concentration. Avoid dispersal of dust in the air (i.e., cleaning dusty surfaces with compressed air). Nonsparking tools should be used. Prevent product from entering drains. See Section 12 for additional Ecological information.

6.3 Methods and materials for containment and cleaning up

Methods for Containment Prevent dust cloud. Cover powder spill with plastic sheet or tarp to minimize spreading.

Methods for cleaning up Avoid dust formation. Take precautionary measures against static discharges. Do not dry sweep dust. Wet dust with water before sweeping or use a vacuum to collect dust. Use personal protective equipment. Take up mechanically and collect in suitable container for disposal. Prevent product from entering drains. Keep in suitable and closed containers for disposal.

7. Handling and storage

7.1 Precautions for safe handling

Advice on safe handling Avoid dust formation. Take precautionary measures against static discharges. Fine dust dispersed in air may ignite. Wear personal protective equipment.

Hygiene measures Handle in accordance with good industrial hygiene and safety practice.

7.2 Conditions for safe storage, including any incompatibilities

Storage Conditions Keep tightly closed in a dry and cool place.

Materials to Avoid No materials to be especially mentioned.

8. Exposure controls/personal protection

8.1 Occupational Exposure Limits (OEL)

8.2 Appropriate engineering controls

Engineering Measures Showers
Eyewash stations
Ventilation systems.

8.3 Individual protection measures, such as personal protective equipment

Eye/Face Protection Safety glasses with side-shields.

Skin and body protection Wear chemical resistant footwear and clothing such as gloves, an apron or a whole body suit as appropriate.

Respiratory protection If irritation is experienced, NIOSH/MSHA approved respiratory protection should be worn. Positive-pressure supplied air respirators may be required for high airborne contaminant concentrations. Respiratory protection must be provided in accordance with current local regulations. NIOSH/MSHA approved respiratory protection should be worn if exposure is anticipated.

Hygiene measures See section 7 for more information

9. Physical and chemical properties

9.1 Information on basic physical and chemical properties

Physical state	Solid
Appearance	Powder
Color	Pink
Odor	Pungent
Odor Threshold	No information available

Property	**Values**	**Remarks • Methods**
pH	Not Applicable	
Melting/freezing point	110 °C / 230 °F	
Boiling point/boiling range	Not applicable	No information available
Flash Point	Not Applicable	No information available
Evaporation rate	Not Applicable	No information available
Flammability (solid, gas)		No information available
Flammability Limits in Air		
upper flammability limit		No information available
lower flammability limit		No information available
Vapor pressure	Not Applicable	
Vapor density	Not Applicable	
Specific Gravity	1.36	
Water solubility	Insoluble in water	
Solubility in other solvents		No information available
Partition coefficient		No information available
Autoignition temperature		No information available
Decomposition temperature		No information available
Viscosity, kinematic		No information available
Viscosity, dynamic		No information available
Explosive properties		No information available
Oxidizing Properties		No information available

9.2 Other information

Volatile organic compounds (VOC) content	None

10. Stability and Reactivity

10.1 Reactivity

No dangerous reaction known under conditions of normal use

10.2 Chemical stability

Stable

10.3 Possibility of hazardous reactions

None under normal processing.

10.4 Conditions to Avoid

Dust formation. Take precautionary measures against static discharges.

10.5 Incompatible Materials

None known based on information supplied.

10.6 Hazardous Decomposition Products

None known based on information supplied.

11. Toxicological information

11.1 Acute toxicity

Numerical measures of toxicity: Product Information

LD50 Oral:	LD50 Dermal:
> 16,000 mg/kg (rat)	> 23,000 mg/kg (rat)

The following values are calculated based on chapter 3.1 of the GHS document

Oral LD50	33,333.00 mg/kg
Mist	55.33 mg/l

Numerical measures of toxicity: Component Information

11.2 Information on toxicological effects

Skin corrosion/irritation
Product Information
• Not a dermal irritant
Component Information
• No information available

Eye damage/irritation
Product Information
• Dust contact with the eyes can lead to mechanical irritation
Component Information
• No information available

Respiratory or skin sensitization
Product Information
• No information available
Component Information
• No information available

Germ Cell Mutagenicity
Product Information
• No information available
Component Information
• No information available

Carcinogenicity
• This product contains <0.1% free formaldehyde and may be capable of outgassing formaldehyde at levels in excess of OSHA's Action Level under some conditions of use. Formaldehyde is a known cancer hazard. Long term exposure may result in dermatitis or respiratory sensitization for sensitive individuals.

Reproductive toxicity
Product Information
• No information available
Component Information
• No information available

STOT - single exposure
No information available

STOT - repeated exposure

• No known effect

Other adverse effects
Target Organs
• No information available
Product Information
• No information available
Component Information
• No information available

Aspiration hazard
Product Information
• No information available
Component Information
• No information available

12. Ecological information

12.1 Toxicity

Ecotoxicity No information available

< 1 % of the mixture consists of components(s) of unknown hazards to the aquatic environment

Ecotoxicity effects

12.2 Persistence and degradability

No information available.

12.3 Bioaccumulative potential

Discharge into the environment must be avoided

12.4 Mobility in soil

No information available.

12.5 Other adverse effects

No information available

13. Disposal Considerations

13.1 Waste Disposal Guidance

Dispose of in accordance with federal, state, and local regulations.

14. Transport Information

DOT	Not regulated
MEX	Not regulated
IMDG	Not regulated
IATA	Not regulated

15. Regulatory information

15.1 International Inventories

TSCA	Complies
DSL	Complies
EINECS/ELINCS	Complies
ENCS	-
IECSC	Complies
KECL	Complies
PICCS	Complies
AICS	Complies
NZIoC	-

TSCA - United States Toxic Substances Control Act Section 8(b) Inventory
DSL - Canadian Domestic Substances List
EINECS/ELINCS - European Inventory of Existing Commercial Chemical Substances/EU List of Notified Chemical Substances
PICCS - Philippines Inventory of Chemicals and Chemical Substances
ENCS - Japan Existing and New Chemical Substances
IECSC - China Inventory of Existing Chemical Substances
KECL - Korean Existing and Evaluated Chemical Substances
PICCS - Philippines Inventory of Chemicals and Chemical Substances
AICS - Australian Inventory of Chemical Substances
NZIoC - New Zealand Inventory of Chemicals

15.2 U.S. Federal Regulations

SARA 313
Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA). This product contains a chemical or chemicals which are subject to the reporting requirements of the Act and Title 40 of the Code of Federal Regulations, Part 372:

Chemical Name	SARA 313 - Threshold Values %
C.I. Basic Violet 11:1, Tetrachlorozincate 73398-89-7	1.0

15.3 Pesticide Information

Not applicable

15.4 U.S. State Regulations

California Proposition 65
This product contains the following Proposition 65 chemicals:

Chemical Name	California Prop. 65
Formaldehyde - 50-00-0	Carcinogen

16. Other information

NFPA	**Health Hazard** 0	**Flammability** -	**Instability** -	**Physical and chemical hazards** -
HMIS	**Health Hazard** 1	**Flammability** 1	**Physical Hazard** 0	**Personal protection** X

Legend:
ACGIH (American Conference of Governmental Industrial Hygienists)
Ceiling (C)
DOT (Department of Transportation)
EPA (Environmental Protection Agency)
IARC (International Agency for Research on Cancer)
International Air Transport Association (IATA)
International Maritime Dangerous Goods (IMDG)
NIOSH (National Institute for Occupational Safety and Health)
NTP (National Toxicology Program)

OSHA (Occupational Safety and Health Administration of the US Department of Labor)
PEL (Permissible Exposure Limit)
Reportable Quantity (RQ)
Skin designation (S*)
STEL (Short Term Exposure Limit)
TLV® (Threshold Limit Value)
TWA (time-weighted average)

Prepared By DayGlo Color Corp.
Regulatory Affairs/Product Safety
Revision Date 23-May-2015
Revision Note
No information available
Disclaimer
The information provided in this Material Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

End of Safety Data Sheet

FORESTRY - STANDARD OPERATING PROCEDURES

Insect & Disease Control - 01

MONITORING, ASSESSEMNT AND CONTROL OF FOREST PESTS

RATIONALE: Using appropriate techniques and tools, populations of major forest pests are monitored, impacts estimated, and control options evaluated to treat only the areas requiring forest protection in an environmentally responsible manner.

BACKGROUND: Pest management can be controversial but is an essential part of proper forest management. Past outbreaks of several forest insect pests have caused extensive & significant damage to the forest resource. Various insect & disease pests have also caused damage & jeopardized intensively managed stands. Pest impacts can also contribute to loss of habitat, to erosion, affect water quality and esthetics, & may increase the risk from wildfires. Outbreaks have necessitated control intervention to minimize these impacts. Effective yet environmentally responsible pest management requires due diligence in detecting, identifying and assessing the problem and responding appropriately through detailed planning to protect forest stands at risk while preventing unnecessary and unintentional application of control methods thereby eliminating or minimizing any possible risk to the public or environment.

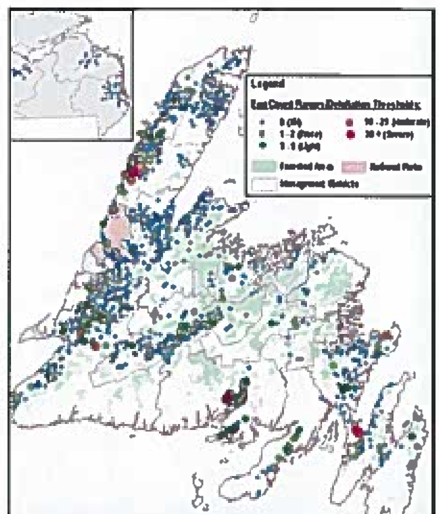
PROCEDURES:

Identification of problem (Monitoring)

a) Use of adequate and appropriate detection and monitoring techniques.
   - pheromone traps detect low-level population trends of various significant insect pests prior to outbreak levels being reached.
   - annual overview aerial reconnaissance and mapping surveys detect current damage/ defoliation.
   - annual fall forecast surveys (using branch samples) are used to predict insect pest activity for the following season.
   - forest health surveys identify pest problems on high-value silviculture areas.

b) Use of diagnostics to determine causal agents and their specific parameters to allow for informed analyses and recommendations.

c) Timely detection and identification of potential risks to the forest are critical in making informed recommendations and taking appropriate action to mitigate impacts.



Hemlock Looper forecast survey points & results.

Increasing trends in pest activity can trigger a pro-active intervention to reduce potential long-term environmental consequences of damage to forest ecosystems as well as forest values relative to intensively managed stands.

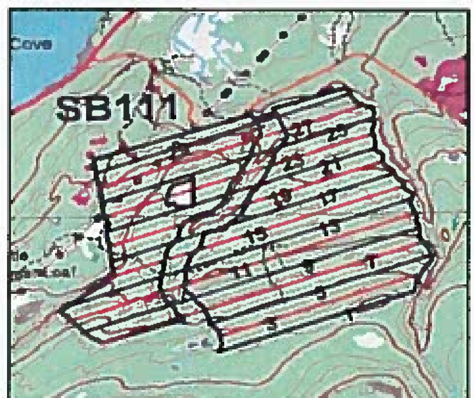
Assessing consequences of problem on environment

- Determine extent and severity of expected pest populations / damage.
- Determine the potential impacts and consequences of the above on the forest.
- Overlay collected data on cover type maps to evaluate effects at the stand level.

- Interpret potential threat and consequences of problem based on knowledge of the pest biology and potential damage from research and experience.
- Use computer software (e.g. ForPRO, DSS) to incorporate pest population information and dynamics with forest inventory data and produce outputs of expected effects on the forest structure.

Planning for protection

- Identify and evaluate potential options to mitigate significant and unacceptable pest impacts on the forest by utilizing an integrated pest management approach. All practical, viable and effective methods are evaluated including the use of pesticides.
- Rank control options based on minimizing pest effects while ensuring an effective and efficient control program with minimal unwanted environmental impacts.
- Outline detailed protection scenarios for areas expecting levels of unacceptable damage or those areas which would result in significant expansion of the problem if not treated.
- Use computer software to provide outputs / consequences of various intervention (control) scenarios from no action up to and including large-scale pesticide application.
- The evaluation of the outputs / consequences allows for recommendations of possible action, level of response, priorization of treatable areas, and resulting outcomes on the forest environment.
- Select the best approved control option(s). Must adhere to the policy of maximizing the level of protection but ensuring the least possible negative effects on the environment. A combination of control options may be considered and utilized depending on the problem and the mitigation of unwanted effects.
- Finalizing treatment areas to only those exceeding tolerable levels of damage or pest population numbers.



Configured treatment block with flight lines and exclusion areas.

In the case of the use of insecticide, particularly aerially applied, the policy is to use those products with a narrow spectrum of effects such as biological products versus broader spectrum chemical products, where there is an effective choice, thereby further minimizing potential non-target risks. For aerial application, the use of current and readily available 'state-of -the-art' delivery and application equipment is essential: appropriate type of aircraft whether rotary or fixed-wing depending on size and location of treatment areas and operational logistics; use of atomizers delivering required droplet sizes; use of *Differential Global Positioning System (DGPS)* navigation hardware and associated software, including Autoboom system to apply the product where required and authorized (respecting buffers and exclusion zones); ensuring pilots are experienced in forest application work and exceeding specified minimum flight hours and treatment hours.

Another critical aspect of planning is the identification and exclusion of sensitive habitat where treatment would not be acceptable. Considerations for exclusion are product specific depending on its toxicity to various non-target species of concern. These habitats/exclusion zones are usually identified through the *Operators Licence* request process, though consultation with agencies and other stakeholders directly affected by the proposed treatment e.g. *Department of Fisheries & Oceans* (scheduled salmon rivers) or particular areas e.g. Provincial parks, wilderness / wildlife reserves, etc. Treatment may be acceptable depending on product or circumstance but has to be approved by regulators and responsible authorities. Usually if permitted, there are strict stipulations in the form of buffer zones (untreated areas between treatment and the sensitive areas). All these concerns must be addressed and are incorporated into the planning process.

More detailed information on elements of this EMS-SOP are contained in the *Insect & Disease Monitoring and Control Manual*.

Insect & Disease Control - 02

PROGRAM OPERATIONS & EQUIPEMENT

RATIONALE: To protect the environment from potential contamination in carrying out operational control programs, especially those involving the use of various aircraft, machinery and pesticides. Significant quantities of fuels, oils, and pesticides are transported to and located at spray bases and must be stored and handled appropriately.

BACKGROUND: Forest pest control operations can vary in size from small ground-based treatments up to large-scale aerial treatments involving multiple aircraft in teams, working from several staging areas (bases). Environmental concerns and potential risks increase in magnitude with the scale of the operations. Attention to protocols and adherence to all applicable stipulations in various regulations, licences and permits is required to avoid contamination of the base(s) or nearby areas particularly those of a sensitive nature (e.g. protected water supplies, water bodies, specific wildlife habitat).

PROCEDURES:

The transport and storage of fuels and oils is regulated by federal and provincial legislation and is outlined in the Department's EMS-SOP "***General - Forest Operations***". Pesticides are strictly regulated by various agencies through their applicable legislation: federally by the ***Pest Control Products Act & Regulations*** and provincially by the ***Environmental Protection Act*** & the ***Pesticides Control Regulations*** administered by the *Department of Environment & Conservation (DE&C)*. A *Pesticide Operator Licence (POL)* with conditions and stipulations covers virtually every aspect of potential risks relative to the environment and the public arising from a control program.

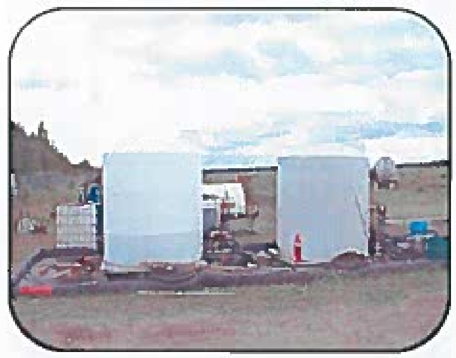
Base Set-up

Control programs require bases from which to work. These can vary in location and requirements depending on the type of operation. For aerial control, this could involve the use of helicopters that can be positioned at remote sites close to treatment areas or at suitable airstrips/airports that are relatively close to treatment blocks. For fixed-wing spray aircraft, a minimum requirement is of an appropriate running surface and surrounding terrain meeting acceptable standards for use, and up to an established airstrip or a designated airport. The operational selection of the specific base depends on factors such as type and size of aircraft to be used, distance to treatment areas, or other logistical constraints. Environmental or airport regulatory restrictions/ space would override operational preference. Bases are equipped with required facilities for hygiene - washroom, shower for decontamination of personnel handling pesticide & related materials/equipment, eye wash station, or first aid equipment in the event of an accident. In addition, adequate supplies of spill clean-up and decontaminating materials are on site and are essential to address any accidental spills arising during the program.

Transport of Pesticides and Fuels Before and During Operations

- Products are transported in approved containers with proper (required) labeling/placarding as per established protocols and regulations.
- Qualified operators (trained and licenced) to transport and handle products.
- All required documentation (WHMIS, MSDS, bills of lading, etc.) at hand.
- Availability and use of approved containment, spill response and emergency equipment if necessary (e.g. shovels, absorbent material, fire extinguishers).
- Spill reporting contact number: fuel volumes>70 L to D.E&C; pesticide volume>100 L of mix or equivalent of unmixed formulation to *Pesticides Control Section* D.E&C **1-800-563-6181** & *Environment Canada* **1-800-563-2444**

Positioning of hazardous materials (e.g. pesticide containers, mixing/holding tanks) at base



- Set back from "runway" to maintain safety distance for aircraft takeoffs & landings.
- Prescribed distance away from all water bodies as per POL.
- Maintain minimum established distances (buffers) from potential at risk (sensitive) areas.
- If possible, position down grade from at risk areas to prevent runoff contamination in case of incident.
- Use of appropriate dyking (composition & containment size) or other stipulated precautions to contain any spill.

Base Operations

- Follow all established guidelines and protocols for safe operations around hazardous products and aircraft/equipment.
- Monitor and record all expenditures of fuels and pesticides to detect any problems (e.g. daily dipping of fuel tanks, metering of pesticide on aircraft (loading volumes) and dipping of aircraft hoppers on return to calculate product expended for each aircraft).
- Routine checking of all storage & holding pesticide tanks to ensure timely detection of any leakage.
- Ensure all equipment (pumps, hoses & fittings, emergency response) are approved/certified for their function and in good working order.
- Immediate containment & clean-up of any spillage as per pesticide label/POL/or specific direction from the DE&C. Spill reporting as per POL, D.E&C.

Dismantling

Appropriate dismantling of bases, clean-up of equipment and site, removal or proper storage of hazardous products, and any required remediation measures are a major component of operational programs. This ensures environmental integrity of the site after the program.

- Decontamination & clean-up of equipment; servicing & storage for next season.
- Clean-up and any remediation at bases.
- Unwanted empty pesticide containers are decontaminated and disposed off as approved by DE&C.
- Contaminated material is neutralized & disposed off as per DE&C.
- Safe and secure pesticide storage in the off-season is important to safeguard against spillage/leakage and potential environmental contamination.
- The POL stipulates the conditions (locked facility, site location, facility construction, warning & contact signage, emergency response materials, copy of the *Contingency Plan*, etc.) for such storage.
- Permission/awareness of municipality of storage facility and contents (for first responders).
- Pesticides are stored in original or other authorized containers with the proper product labeling.
- Fuels are generally not stored during the off-season.
- (e.g. shovels, absorbent material, fire extinguishers).
- Spill reporting contact number: fuel volumes>70 L to D.E&C; pesticide volume>100 L of mix or equivalent of unmixed formulation to *Pesticides Control Section*. D.E&C **1-800-563-6181** & *Environment Canada* **1-800-563-2444**

More detailed information on elements of this EMS-SOP are contained in the *Insect & Disease Monitoring and Control Manual*.

Newfoundland Labrador

Insect & Disease Control - 03

CONTROL OPERATIONS

RATIONALE: To ensure appropriate, timely, effective & environmentally responsible target specific control (including the use of pesticides) on specific stands where pest levels exceed tolerable thresholds. Control is conducted to prevent tree mortality and growth loss and to preserve the forest ecosystem while minimizing inappropriate pesticide application on non-target areas.

BACKGROUND: The requirement for and use of pesticides, especially for larger scale aerial programs, requires due diligence in assessing the overall need, adherence to and compliance with all legislation, and acquisition of appropriate licences and permits due to the sensitive nature and need to minimize any associated potential risks.

PROCEDURES:

Biological Assessment

a) Assess pre-treatment pest population levels

Determine if sufficient population levels are present as per forecast to warrant control. If not, then control cancelled or modified as necessary. Other factors influencing the final decision are previous tree damage, priority of area, etc.

b) Assess post-treatment pest population levels

Determine pest levels after treatment interval (if more than one application is permitted and prescribed, post-application numbers may dictate if further control is necessary. If numbers are sufficiently reduced, a second application may not be required, thus saving product, reducing any potential risk from additional application and any potential contamination and/or environmental concerns, etc.

c) Final assessment of program to determine program success and the potential need for possible future intervention (i.e. evaluation of pre and post -spray survey results).

Treatment

All personnel involved in the handling and supervising of pesticides and related products are appropriately trained/licenced, e.g. Applicator Licence/Pesticide Licence, WHMIS, Dangerous Goods, OH&S, DNR IDMC staff oversee and verify all aspects of the treatment as follows.

a) Calibration of spray aircraft and equipment is critical to ensure correct pesticide dosage & droplet size from spray equipment (i.e. atomizers, nozzles) and proper functioning of computerized navigation (AgNav or equivalent system) and delivery systems thereby maximizing control effectiveness and minimizing environmental concerns. Navigation files of preprogrammed flight lines/ cutouts are sent to aircraft contractor for compatibility with the aircraft systems. For more information on calibrating equipment, refer to the *Forest Insect & Disease Monitoring and Control Section Operating Procedures Manual.*

b) General weather check to assess suitability of existing and forecast weather to carry out control mission. Weather parameters for treatment are stipulated on pesticide label and in the Pesticide Operator Licence. If aircraft are being utilized, weather conditions for flying are also critical, i.e. Visual Flight Rules (VFR) good visibility, no fog concerns, etc.

c) *Treatment site check*

- Check local weather conditions at block (weather could differ from forecast or e.g. from airport depending on the distance between the two)
- Pre-treatment reconnaissance of spray blocks identify any potential hazards not previously known or any transient (e.g. campers, hikers, berry pickers) or environmental concerns.

Parameter[1]	Stipulated Value(s)
Wind Speed	Between 2 – 10 km / hr
Air Temperature	< 25 °C
Relative Humidity	> 50 %
Rain	None or not forecast within the next 2 hours
1 Exceptions to these general weather parameters may be granted on a case-by-case basis from the Pesticides Control Section, Dept. Environment & Conservation.	

d) *Supervision of treatment*

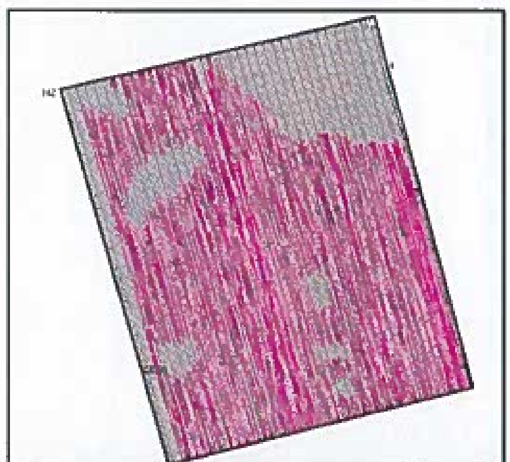
- Advise pilots of any identified hazards.
- Ensure flight line adherence as predetermined.
- Ensure flight height above canopy.
- Ensure no-treatment cutouts / exclusion areas are maintained.
- Ensure spray atomizers are emitting product uniformly (no blocked or dripping / leaking units when not treating).

e) *Aircraft incidents (jettison of product; crash)*

- Stipulations / protocols as per *Pesticide Operator Licence / Contingency Plan*: containment & recovery of product; absorption & removal of spill material; decontamination of site in full consultation with and approval from the Department of Environment & Conservation.

f) *Post-treatment Application Assessment*

- Determine amount of product emitted (using both on-board aircraft meter readings and tank / hopper dip-sticking) to compare with prescription to ensure proper dosage was applied.
- Review digital information of mission from navigation system to verify proper treatment.
- Hold debriefing with pilots and ground personnel to discuss any issues that need to be resolved to maintain high standards of operation.
- Implement all corrective measures as required.



Printout of block treatment showing actual application (colored portion) and cutouts / no-treatment (gray)

More detailed information on elements of this EMS-SOP are contained in the *Insect & Disease Monitoring and Control Manual*.