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Challenges to IPM Advancement: Pesticides, Biocontrol, Genetic Engineering, and Invasive Species.

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Abstract

Integrated pest management (IPM) is widely promoted as the most sensible method of sustainable control of important agricultural pests. However, IPM is not widely practiced in commercial crops where this technology could be utilized. In crops where IPM is used, the sophistication of programmes with respect to the numbers of species, types of pests, and variety of control tactics simultaneously implemented are often simplistic and continued development of existing programmes for greater sophistication and management of multiple pest complexes is extremely challenging thus making progress slow. This situation for IPM may become more difficult to resolve in New Zealand, and elsewhere, as difficult and controversial pest management issues related to pesticide use, importation and utilization of exotic natural enemies, deployment of transgenic crops, invasive species, and a diminishing base of scientific talent and research funding become increasingly apparent and demanding of attention and resolution.

Introduction

Integrated pest management (IPM) had its genesis in the mid to late 1950's when the detrimental effects of pesticide overuse became increasingly apparent. Continual and often excessive and unnecessary use of synthetic halogenated hydrocarbons were identified as the cause of resistance development, pest resurgence, the elimination of natural enemies that resulted in secondary pest outbreaks, pollution of water supplies, and lethal and sub-lethal impacts on charismatic wildlife (e.g., egg shell thinning in raptor species caused by DDT). Rachel Carson's (1962) landmark book "*Silent Spring*" identified these problems, and raised the alarm about the unintended consequences of agricultural pesticide use, which ultimately gave these issues widespread and permanent public and political recognition.

IPM or "integrated control" was "officially" conceived in seminal work by University of California researchers (i.e., Vern Stern (UC Riverside), Robert van den Bosch (originally UCR then UC Berkeley), Ray Smith (UCB), Ken Hagen (UCB), and Carl Huffaker (UCB)) that culminated in the landmark Hilgardia publication by Stern *et al*. (1959). However, some of the concepts formalized as essential cornerstones for IPM programmes were not novel, having been employed routinely by agriculturists prior to the invention and wholesale adoption of synthetic pesticides in the late 1940's (Kogan 1998). The most common practice employed by pre-IPM farmers that forms a prominent cornerstone of modern IPM programmes is the exploitation of natural control, that is, the preservation and enhancement of resident natural enemies of pest species inhabiting crops. The strategy of deliberately manipulating generalist predator populations for pest control (e.g., ants and spiders) in some cropping systems (e.g., citrus (China) and dates (Yemen)) is hundreds of years old (Van Driesche & Bellows 1996). Upper trophic level organisms are primarily relied on for pest control in IPM, however, when scouting of key pest species indicates pest densities are approaching an *a priori* action threshold; carefully timed applications of pesticides are made to prevent economic injury to the harvestable product. Thus within the idealized IPM paradigm, biological and pesticidal control are "complementary" and can be utilized "harmoniously" (Kogan 1998). This synergism between natural and synthetic control can result in greater profitability for growers, improved environmental stewardship of farmland and surrounds, and sustainable management of organisms notorious for developing pesticide resistance. Despite the social, political, and intellectual appeal of the IPM approach to managing agricultural pest problems, widespread adoption and development of increasingly sophisticated IPM programmes that simultaneously manage several classes of pests (e.g., insects, mites, phytopathogens, and weeds) in diverse agroecosystems has generally not occurred to any significant extent (Kogan 1998). In many agricultural systems, the majority of IPM programmes target only one or two pests (e.g., mites and thrips that can be controlled with the same insecticide (e.g., abamectin) and are attacked by the same suite of generalist predators (e.g., phytoseiid mites)) or a pest complex (e.g., leaf rollers). While development of some IPM programmes has progressed significantly in some crops and countries, especially in relation to crops of high market or export value (e.g., kiwifruit and pip fruit production in New Zealand) the overall global situation for IPM has not changed greatly despite 50 years of research (Kogan 1998). Many of the impediments to IPM implementation and increased sophistication identified by Wearing (1988) are still relevant today, and the challenges for IPM are increasing, more varied, and for New Zealand agriculture, strongly influenced by overseas market trends (Whalon & Penman 1991). I perceive five major and interconnected factors affecting future IPM development, adoption, and sustainability: (1) pesticides, (2) biological control, (3) transgenic crops, (4) invasive pest species, and (5) recruiting, training, and retaining excellent IPM researchers and extension personnel, and providing productive programmes with stable moderate to long term funding for research and outreach.

Pesticides

Contamination of food and water and the psychological dependence of growers on chemicals for pest control are the consequences of over-reliance on pesticide applications in modern agriculture (van den Bosch 1978). In the highly controversial "The Pesticide Conspiracy" van den Bosch (1978) raises one extremely salient and poignant argument – the right of every consumer to "molecular privacy," this being the right to eat food without synthetic residues that accumulate and/or have an unwanted effect in the consumer's body. Given the litigious nature of U.S. society it is surprising that more lawsuits have not been filed on behalf of victims that have suffered "catastrophic" health consequences (perceived and realized) from agro-chemical residues on food that compromised their "molecular privacy." The classic example of this kind of public outrage over perceived hazard from synthetic compounds was to Alar®, daminozide, a plant growth regulator used in apples in the U.S.A. (Rosenberg *et al*. 2001). Because of safety concerns over synthetic compounds being applied to foods, many broad-spectrum pesticide products (e.g., carbamates and OP's) with known or suspected risks to human health are being phased as part in several countries (e.g., New Zealand and U.S.A.) as a result of legislation that is aimed at protecting food quality and consumer health.

A growing body of scientific evidence coupled with experimental research is documenting the subtle but serious health consequences when "molecular privacy" is violated by exposure to trace residues (e.g., parts per billion) of some pesticides (Colborn *et al*. 1997; OSF 2005). Extremely small amounts of pesticide residues or byproducts of their environmental degradation can act as endogenous hormonal analogues adversely affecting development and behaviour in vertebrates (e.g., atrazine on amphibian development (Storrs & Kiesecker 2004)), including humans (e.g., endosulfan on the male reproductive system {Saiyed *et al*. 2003})). Accumulating knowledge of these phenomena led to the development of a revolutionary new biological theory – the environmental endocrine hypothesis (Krimsky 2000). Investigation of hormonal activity focuses on the tenet of how little of a compound is needed for an observed endocrine effect and is diametrically opposed to the cancer screening paradigm which assesses how much is needed to cause an adverse health effect. Overwhelming evidence for hormonal mimicry has led the U.S. Environmental Protection Agency (EPA) to mandate testing of new synthetic compounds for hormonal activity before wide-scale use outside of the laboratory (Wu 1998). Obviously, the need for protective chemistries that can aid crop production while not adversely affecting the consumer or other non-target organisms are needed in agriculture. "Reduced-risk" pesticides may be alternative chemistries that can obviate problems associated with more conventional pesticides used in agriculture. Addressing these well recognized health and environmental concerns should encourage the development of IPM programmes.

The U.S. EPA defines a low-risk insecticide as one that "may be reasonably expected to accomplish one or more of the following": (1) reduce pesticide risks to human health; (2) reduce pesticide risk to non-target organisms; (3) reduce the potential for contamination of valued environmental resources, or (4) broaden adoption of IPM or makes it more effective (EPA 1998). Often insecticides will be registered as reduced-risk because they have very low toxicity to humans (Crafton-Cardwell 2002). Insecticides registered for reduced-risk status in some California crops (e.g., citrus) include amongst others spinosad (a neurotoxic insecticide produced by fermentation of an actinomycete) and pyriproxyfen (an insect growth regulator that mimics juvenile hormone). Estimation of the adverse or negative impact that reduced-risk pesticides can be expected to have on IPM programmes prior to introduction and large scale use can be difficult to predict *a priori*, but is generally assumed to be negligible because of "reduced-risk" registration status.

However, there is a growing body of literature that indicates that the interaction of certain reduced-risk pesticides with key natural enemies may not be benign and may be responsible for substantial disruption of long-term biological control of key pests (Crafton-Cardwell 2002, Johnson & Krugner 2004). Pyriproxyfen use in South Africa has severely disrupted biological control of scale pests in citrus by coccinellids (Hattingh & Tate 1995) and a similar adverse effect has been observed in California U.S.A. where cottony cushion scale (*Icerya purchasi* Maskell (Hemiptera: Margarodidae)) control by *Rodolia cardinalis* Mulsant (Coleoptera: Coccinellidae) has been reduced after almost 120 years of excellent and continuous control (Crafton-Cardwell 2002). Registration of pyriproxyfen in California was largely driven by grower demand to control red scale, *Aonidiella aurantii* (Maskell) (Homoptera: Diaspididae), a pest difficult to control with conventional registered chemistries.

The impact of Spinosad on beneficial organisms may similarly not be inconsequential and detrimental effects on natural enemies that are key regulatory agents in IPM programmes have been observed in laboratory and field studies (Cisneros *et al*. 2002, Williams *et al*. 2003). Hymenopterous parasitoids are extremely sensitive to intoxication by spinosad (Tillman & Mulrooney 2000; Williams *et al*. 2003; Schneider *et al*. 2004) as are some generalist predators, including big-eyed bugs, (*Geocoris punctipes* (Say) (Hemiptera: Lygaeidae)) (Tillman & Mulrooney 2000), earwigs (*Doru taeniatum* (Dohrn) (Demaptera: Forficulidae)), pirate bugs (*Orius insidiosus* (Say) (Hemiptera: Anthocoridae)), and some coccinellids (Galvan *et al*. 2005, Williams *et al*. 2003). Generally, laboratory and field data evaluating toxicity of spinosad suggest that predators are less vulnerable to poisoning than parasitoids (Williams *et al*. 2003). Important crop pollinators such as undomesticated bumble bees (*Bombus* spp.) may suffer sub-lethal effects from spinosad residues when applied at recommended field rates. Spinosad can taint pollen which is collected and fed to developing larvae. Bee larvae that consume spinosad as part of their diet complete development but are poor foragers in comparison to non-exposed bees which reduces pollination of crops (Morandin *et al*. 2005).

Abamectin is a bacteria-derived pesticide that is used in some IPM programmes for controlling mites and thrips because of its selectivity. In California-grown avocados, abamectin is combined with narrow range petroleum oils that give abamectin translaminar activity. Once inside the leaf, the insecticide is protected from u.v.-degradation and direct residue contact with natural enemies is eliminated. Following applications of abamectin for avocado thrips control (*Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae)), key natural enemy populations (i.e., *Franklinothrips orizabensis* Johansen (Thysanoptera: Aeolothripidae)) diminish (Silvers 2000). Mortality from dried residues appears not to come from contact but because of supplementary leaf-feeding by predatory thrips which results in the ingestion of abamectin that has moved into treated leaves (Hoddle 2003).

Reduced-risk pesticides are a major step forward in reducing environmental hazard associated with insecticidal management of agricultural pests. However, wide scale implementation of reduced-risk pesticides within an IPM framework should only be considered after laboratory assays have been conducted and "safety" confirmed with replicated multi-year field trials in target cropping systems where pest and natural enemy numbers are monitored closely. Promising products may not necessarily need to be discarded following field evaluations in which unacceptable non-target impacts were observed. Increased knowledge of non-target ecology and behaviour coupled with modification of timing, dose, and formulation may need to be better understood and managed in order to maximise pesticide efficacy and minimise harm to beneficial organisms. Reconciling pesticide use practices and natural enemy biology so the two are compatible adds extra layers of complexity to sensibly using reduced-risk pesticides. Complicated pest management practices are seldom embraced by growers even when presented as part of a sustainable and cost effective IPM program. Encouraging change from simplistic to more demanding management strategies is especially difficult when the “in the old days one spray took care of everything” mentality is encountered.

Construction of publicly accessible national pesticide usage databases

Construction and maintenance of pesticide use databases that are publicly accessible and provide usage statistics by active ingredient, application amounts, commodity, and area within a country are immensely useful in assessing pesticide application habitats and trends. New Zealand takes pride in its clean-green image, a world-recognized quality that is often remarked upon by people who have not visited the country. Such a wholesome view of New Zealand is extremely desirable and has been carefully cultivated and promoted when marketing agricultural commodities in highly competitive overseas markets, especially Europe and the U.S.A. A major shortcoming in assessing the strength of New Zealand’s clean-green label is an inability to assess the factualness of this claim. New Zealand has no transparent and publicly accessible national pesticide databasing system that is regularly updated to substantiate the validity of low pesticide risk exposure from food that is part and parcel of the projected clean-green image that is advertised.

The California Department of Pesticide Regulations (CA-DPR) has a web-accessible pesticide database for the state of California. Pesticide record keeping has been mandatory since 1989 and data are used to assess dietary risk arising from pesticide exposure, estimating water and air pollution from pesticides, and designating protection from pesticides of vulnerable habitats and endangered wildlife (CA-DPR 2005). The CA-DPR database records the amount of active ingredient applied on a per hectare basis according to commodity, county, and chemical class. The database is particularly useful for investigating factors affecting pesticide applications on a yearly basis. For example, crop market values increase, pesticide use increases to protect crops of increasing value; pesticide use declines may be correlated with drought and decreased acreage planted; herbicide use increases following heavy winter rains because of greater weed growth. With such summary information, overall usage statistics can be estimated to determine if pesticide use is increasing, decreasing, or remaining static and what factors are driving these trends. The CA-DPR database and mandatory pesticide record taking may be a good model for New Zealand to consider adopting and modifying for its unique agricultural systems thus bringing important data on pesticide use patterns to the public domain. This would allow the clean-green paradigm to be independently verified or refuted with data. In support of this idea, a recent report on pesticide use trends in New Zealand recommended strongly that a more rigorous method of recording pesticide sales and use data is needed. This would allow better understanding of increasing pesticide usage statistics in agriculture, especially horticulture, which has seen some of the greatest increases in pesticide use as growing acreage has expanded despite increased development and implementation of IPM programmes and use of reduced risk pesticides (Manktelow *et al*. 2005).

Biological control

Biological control is considered to be the most important component of an IPM program. Typically, new exotic pests that invade and become problematic may become the targets of classical or inoculative biological control programmes. In this instance, the home range of the new pest is explored and potential natural enemies are returned to quarantine, assessed, and if data indicates they are efficacious and host specific, regulatory authorities are petitioned for permission to release.

Alternatively, if the pest has been the target of biological control elsewhere, foreign exploration may be unnecessary as cooperators working with natural enemies of interest in the country of recent release can be contacted and asked to send shipments of biological control agents for further study in quarantine.

Since its inception, biological control of weeds and arthropods has been viewed as an environmentally friendly method of managing exotic pests. The benefits of this technology are touted as being cheap and sustainable, safe to humans, not causing appreciable adverse non-target impacts, nor are natural enemies seen as a source of biological pollution (Hoddle & Syrett 2002, Hoddle 2004a,b,c). However, growing disquiet from prominent ecologists and taxonomists with well researched examples indicate that in some instances unwanted declines of native flora and fauna have occurred, in part, because of the actions of deliberately imported and released exotic natural enemies (Louda & Stiling 2004).

As a consequence of documentation of non-target impacts and the tarnishing of biological control as a safe form of pest control, the era of self-regulation of arthropod natural enemy importation, evaluation, and release by practitioners is drawing to a close. New Zealand's HSNO Act has set the world's highest safety standards and has attracted considerable attention internationally as being recognized as legislation that is very focused on preserving environmental integrity. The implementation of the HSNO Act and the process by which it reviews biological control programmes through ERMA NZ has been observed nationally and internationally with interest. In Australia, biological control agents are regulated by two agencies under three separate Acts, and has been similarly heralded as a thorough and biosafety-conscious approach. The U.S.A. and Europe are moving towards developing more stringent guidelines governing natural enemy importations, evaluations, and releases. While the legislative goal of increased safety of biological control is commendable, the concern over increased expenditures and time associated with natural enemy evaluations are valid as these impediments may reduce the number of viable targets selected for biological control and increased pesticide usage may be the only feasible cost effective option in the absence of efficacious natural enemies. The impact of evolving regulatory biological control legislation on IPM program development may severely hamper incipient IPM programmes that would benefit from importation and release of exotic natural enemies. This scenario could occur because industry may not be able to easily and cost effectively pursue the biological control option thereby removing it as an IPM cornerstone which could possibly lead to greater reliance on pesticides for control of key pests.

Transgenic crops

"*…I criticize modern chemical control not because it controls harmful insects, but because it controls them badly and inefficiently, and because it creates many dangerous side effects in doing so.*
…We are capable of much greater <u>*sophistication*</u> *in our solutions to this problem.*" (Carson 1968). With this statement from 'Silent Spring' in mind, an interesting and pertinent question is: are genetically engineered crop plants the "sophisticated solution" envisioned by Carson for managing insect pests; or is this technology replete with analogous problems already identified for many pesticides currently used in agriculture? The introduction of genetically engineered crops has resulted in significantly greater scrutiny and a need to address concerns that were of much lower importance in conventional cropping systems. These concerns include food and environmental safety, protection of biodiversity outside of agricultural areas, and gene flow into progenitor populations and weedy crop relatives.

Genetic engineering (GE) and widespread planting of crop plants that express genes producing insecticidal toxins derived from *Bacillus thuringiensis* Berliner or those that confer immunity from herbicides is extremely controversial in Europe, but much more accepted in the U.S.A. Some agricultural sectors of New Zealand may gain a potential economic advantage over competitors by promoting a GE-free image to develop niche markets in countries with high public opposition to GE food. Such "value added" exports may potentially be very lucrative and seen as the "riches of a clean green land" (S. Wratten pers. comm. 2006). A moratorium on GE crops in New Zealand was lifted in late 2005 and technology moved from the laboratory to the field as experiments with transgenic potatoes and onions commenced to assess the utility of GE crops for managing pests under New Zealand's unique growing conditions. Despite the expected potential benefits to New Zealand agriculture (Teulon & Losey 2002) public resistance to this technology is likely to remain despite promotion of the environmental and economic benefits of GE because of concerns of unintended impacts that may effect precious native wildlife or human health.

Debate over the adverse environmental impact of genetically engineered plants was brought to widespread public attention with published studies on monarch butterfly larvae, *Danaus plexippus* L. (Lepidoptera: Nymphalidae), on milkweed plants being poisoned by corn pollen expressing *Bt* δ endotoxins (Losey *et al*. 1999). Controversy escalated when research into tritrophic interactions between transgenic plants, herbivores that have ingested toxins, and natural enemies attacking these poisoned pests raised issues concerning ecological compatibility and sustainability of these systems (Hilbeck *et al*. 1998a,b). Subsequent work has clearly demonstrated that flagship species like monarch butterflies are not at appreciable risk from *Bt* intoxication (Pleasants *et al*. 2001, Sears *et al*. 2001) and tritrophic interactions do not have appreciable impacts on upper trophic level organisms (Dutton *et al*. 2003) which have been verified by long term field-based population studies (O'Callahagn *et al*. 2005). Consequently, all research to date on commercialized *Bt* crops indicates that the expressed Cry toxins do not have any direct effect on species belonging to orders other than the target insects (Lepidoptera or Coleoptera) (O'Callaghan *et al*. 2005). This is not surprising given the long history of safe and very targeted use of microbial *Bt* products (Glare & O'Callaghan 2000).

Thus, *Bt*-transgenic crops have the potential to be a viable alternative to conventional insecticides. Around the globe, deployment of transgenic crops expressing *Bt* have consistently resulted in significant reductions in insecticide applications. For example, pesticide use dropped by 80% in transgenic rice crops grown in China, yield increased by 6%, and pesticide poisonings of humans were eliminated (Huang *et al*. 2005). In cases where *Bt* crops replaced the use of conventional insecticides (e.g., cotton or sweet-corn) for key pest control, substantial positive effects on the natural enemy fauna have been reported. This has resulted in increased biological control of potential secondary pests such as aphids and stink bugs that normally required sprays for control (Green *et al*. 2001, Reed *et al*. 2001, Wu & Guo 2003). Thus *Bt*-transgenic crops appear to promote the conservation of biological control agents for key and secondary pests in cropping systems by eliminating the need for broad spectrum insecticides, and this has provided increased opportunities for biological control thereby providing a very important tool for IPM programmes which rely on natural enemies for pest control (Green *et al*. 2001, Wu *et al*. 2002).

Transgenic crops may not be entirely risk free. Major risk assessment work on GE crops is now focusing on transgene escape and the probability of spread and persistence of transgenes into wild plant populations (Ellstrand 2001), and the potential ramifications of gene escape and introgression (Vacher *et al*. 2004). Despite the controversy over GE crops, Europe is now moving towards adoption of this technology and the European Union and European Community are drafting guidelines and legislation on use of GE crop plants. GE maize and oilseed rape has been approved for use and added to the EU Common Seed Catalogue (Black 2004). Incredibly, France, a country notoriously contrary to international opinion and U.S. technological innovation is assessing GE wine grape varieties for control of Fanleaf disease which is vectored by a soil nematode. A major motivation for potential deployment of GE grapes in France is to restore the wine industry's competitiveness against countries such as New Zealand (Anon 2004).

Resistance development to *Bt* crops expressing toxins coded by single Cry genes has not been observed in the U.S.A. despite ~10 years of use and exponentially increasing acreage of cotton and corn being planted with GE crops expressing *Bt*. The reasons for no detectable increase in *Bt* resistance by key pests is due in part to *Bt* free refuges, continuous high dose production of toxins, and increased fitness costs associated with resistance (Tabashnik *et al*. 2005). With the development of increasingly sophisticated GE crops that rely on multiple genes to code for different toxins coupled with carefully managed planting strategies (i.e., mandatory refuge plantings) the specter of resistance development to *Bt* and GE crops in general may be reduced even further.

It would appear that in Europe, and elsewhere, public resistance to GE crops is waning, major ecological perturbations resulting from non-target impacts and resistance development have failed to be realized in field situations. The effect of transgene escape that could foster invasiveness by releasing hybrids from genetic and ecological constraints is still under intense scrutiny. In the emerging favorable climate on GE crops, sectors of New Zealand's agriculture that adopt a GE-free stance may not be commercially sustainable and non-GE crops treated with conventional insecticides may, in the future, face greater marketing resistance in Europe and the U.S. as the benefits associated with GE crops becomes more readily accepted by a wary public and GE becomes synonymous with reduced-risk IPM, and decreased levels of harmful pesticide residues.

Invasive species

Exotic species constantly lurk outside of country borders threatening invasion. When successful incursion occurs it is almost always to the detriment of existing IPM programmes as growers resort to pesticides to treat the new key pest thereby upsetting biological control and disregarding action thresholds for previous key pest species. For example, historically, pesticide use in California avocado orchards has been minimal. Important pests have been kept below economically injurious levels by natural enemies. Until relatively recently, California avocado production was world-renowned because it relied almost exclusively on biological control for suppression of noxious pests (McMurtry 1992).

The importance of natural enemies for avocado pest control has been slowly eroding in California. This declining trend began in 1982, when red-banded whitefly, *Tetraleurodes perseae* Nakahara (Hemiptera: Aleyrodidae) established in San Diego County. Persea mite, *Oligonychus perseae* Tuttle, Baker & Abbatiello (Acari: Tetranychidae) was discovered attacking avocados in San Diego in 1990. In 1996, avocado thrips, *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae), was discovered almost simultaneously in orchards 160 km apart in Ventura and Orange Counties. In 2004, avocado lace bug, *Pseudacysta perseae* (Heideman) (Hemiptera:Tingidae), and *Neohydatothrips burungae* (Hood) (Thysanoptera: Thripidae) were discovered on avocados in San Diego County. Over a period of approximately 22 years (1982-2004), five new avocado feeding insects established in California, at approximately 8 year intervals (Hoddle 2005).

The effect of these invaders has been catastrophic. *Scirtothrips perseae* alone costs the California avocado industry $4-5 million (US) per year now that the industry has adjusted to the initial insult and developed reliable control strategies (Hoddle *et al.* 2003). The net result of these invasions has been the near total abandonment of IPM for avocado pests and almost universal adoption of reduced-risk pesticides (e.g., spinosad and abamectin combined with highly refined petroleum oils) for control of the two most damaging pests, *S. perseae* and *O. perseae*. Resistance development is being monitored and increased tolerance by key pests to these compounds has been observed (J. Morse pers. comm. 2005). Another effect on managing these exotic invaders has been the overall increasing use of insecticides (Fig. 1) on avocados, a trend counter to most other agricultural crops in California where pesticide applications have been declining.

Development of sustainable management programmes for the key pests *S. perseae* and O. *perseae* will need to rely on judicious pesticide use. The potential for classical biological control of these pests is not promising as invasive tetranychid mites and thrips are usually not well regulated by natural enemies and inoculative natural enemy releases are prohibitively expensive. There are no concerted efforts to develop new resistant avocado cultivars either via traditional breeding or GE to replace the highly susceptible 'Hass' variety. The resident exotic pest phalanx (more additions (e.g., fruit feeders) can be expected in upcoming years) has significantly affected the economic viability of California-grown avocados. Management expenses (i.e., employment of pest monitoring scouts and aerial pesticide applications) associated with these incursive species coupled with cheap imported avocados from New Zealand, Mexico, Chile, and the Dominican Republic, highly restrictive use of pesticides, expensive water and land costs may portend the long-term demise of California's avocado industry.

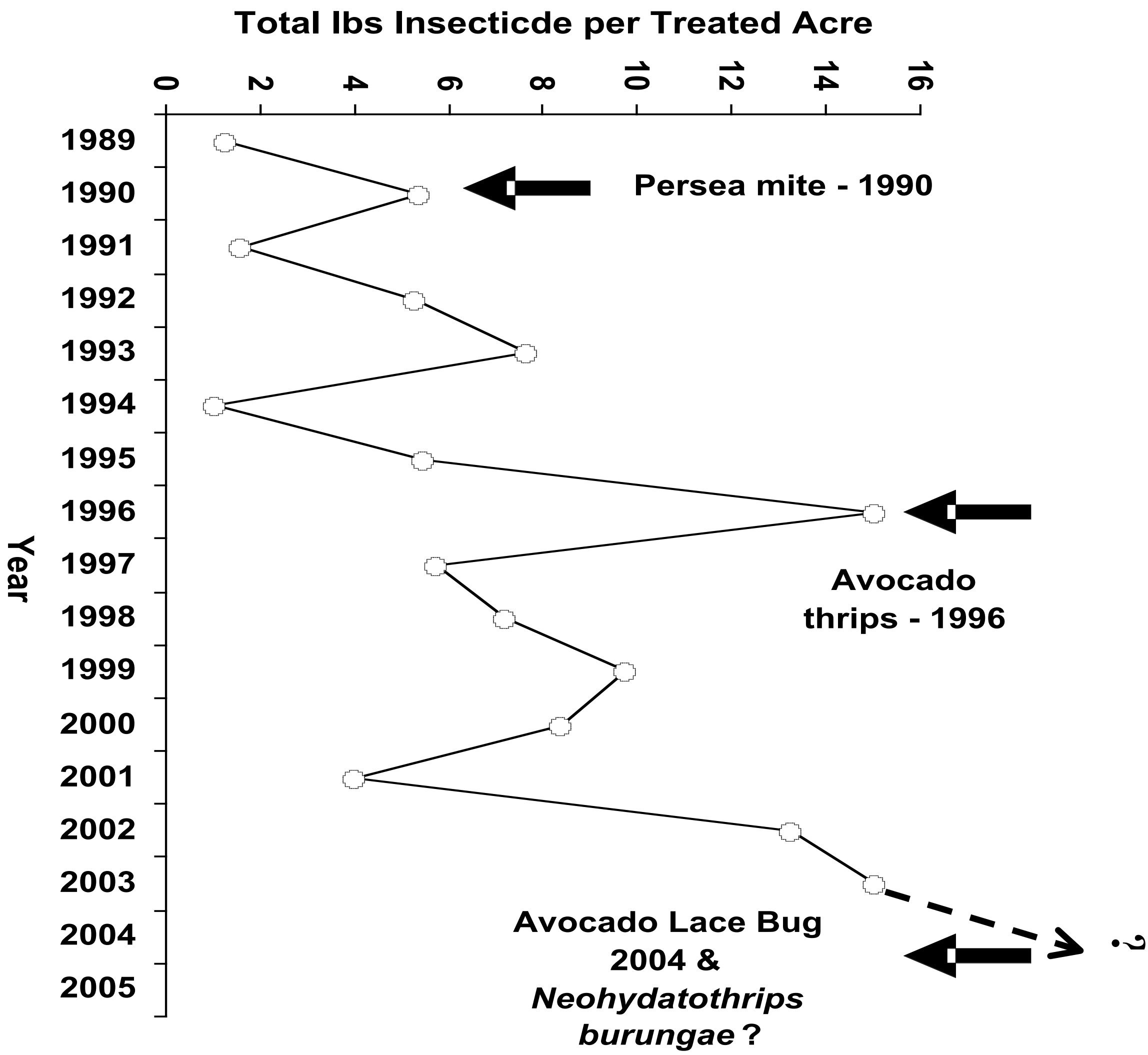

Fig. 1. Total pounds of insecticide applied per treated growing acre of avocados combined for San Diego and Ventura Counties. Acreage and insecticide application data were obtained from the CA DPR website (http://www.cdpr.ca.gov/index.htm). Arrows indicate years in which exotic avocado pests established in California after the CA DPR initiated mandatory pesticide record keeping in 1989. At the time of writing pesticide records for California were available only through 2003. Pesticide usage may continue in an upward trend for 2004 and 2005 as two new insects feeding on California avocados were discovered in 2004.

Increasing the talent pool and research funding

The challenges to IPM development and implementation (i.e., addressing pesticide use, biological control, transgenic crops, and invasive species), individually and combined, provide important and exciting research opportunities for New Zealand's emerging scientific talent. The current Labor Government is attempting to reverse New Zealand's well recognized "brain drain" by screening potential post-graduate candidates from 15 countries for scholarship awards and training in New Zealand Universities (Savage 2005). Taxpayer dollars will also help subsidize non-scholarship students to lure top candidates to New Zealand to pursue higher education and research that could benefit the country (Quirke 2005). The idea behind this government program is to recruit "top-knotch" individuals to conduct relevant research that will benefit New Zealand. This model has worked extremely well in the U.S.A. and it is a well recognized fact that imported highly educated talent has kept the U.S.A. a world-leader in many scientific endeavors, including pest management.

In addition to these recruitment incentives, plentiful opportunities exist in excellent overseas universities to which New Zealand government and/or industry sponsored students could be trained and then encouraged to return to New Zealand on a retainer program. A program like this is currently operating in Singapore. Selected students are trained at a University of their choice, tuition fees, airfares, sundry expenses, and a salary are paid during 5-yr Ph.D. programmes. Successful applicants must commit to working for 6-yr after graduating (Lee 2005). Recruitment of foreign researchers and overseas training of Kiwis will only be successful in the long-term if the "brain-drain" of newly minted researchers can be prevented, and top quality scientists retained for the long-term benefit of New Zealand science. The best way to assure retention of dedicated and productive scientists is through adequate compensation for measurable effort and productivity, and secure funding of programmes that show tangible progress and benefits to the client base being served. Job insecurity, funding uncertainty, vacillating project goals, and unexpected departures from mission objectives can be unsettling and lead to poor productivity, program stagnation, and loss of skilled employees; which collectively may take considerable time to recover from. Government and commodity investment in research is obviously needed, but an additional element must be added to any successful research program that expects implementation and adoption. This essential last element in moving research into the farmer's hands is the domain of the Extension Specialist. Ensuring results from practical pest management research are adopted and effectively used can only be achieved through an efficient information transfer operation. Extension efforts are very successful when highly trained "teachers" can explain, demonstrate, encourage, and promote adoption of novel cost effective and beneficial IPM technologies.

Conclusions

IPM development and implementation in New Zealand and elsewhere face continuous hurdles which arise either as issues relating to sustainable pesticide use; increasing regulatory obstacles regarding use of exotic natural enemies for control of important agricultural pests; the public and political rift caused by transgenic crop plants and the pest management benefits this technology offers and the potential environmental problems that could arise from the unintended spread of transgenes; and the continuous threat posed by invasive pests (arthropods and pathogens). In many instances the full potential of IPM is not being realized as pesticides are still the control option of choice and alternative supplementary technologies such as biological control and GE crops are stigmatized as being bad for the environment (i.e., non-target impacts and food web perturbations caused by natural enemies) or bad for human health (i.e., hysteria over Franken Foods).

If New Zealand agriculture is to fully embrace IPM and promote "clean green" produce then greater accountability for pesticide use is going to be required if the wholesome and healthy image is to be promoted successfully and honestly when pushing for access to niche markets for agricultural produce. In this instance, pesticide record keeping must be reliable and independently verified as accurate. Data collection and analysis of pesticide use must be transparent and made publicly accessible on the web. Unacceptable pesticide residues on food in the future will most likely include synthetic compounds that have demonstrated hormonal activity (e.g., endosulfan) and data on use of such compounds is going to be required by importing countries. Restrictions on natural enemy importations and releases will necessitate greater research efforts on resident natural enemies (exotic and native) for enhanced efficacy either through augmentative or conservation biological control. Biosecurity practices need to be enhanced to reduce the rate at which exotic pests enter New Zealand: prevention is better than the cure.

The future of IPM and development of innovative pest control programmes in New Zealand is going to lie with highly trained and motivated scientists and extension personnel who are regularly exposed to the ebbs and flows of international thought and opinion. Scientists must be willing to challenge the status quo and prevailing paradigms when appropriate to initiate meaningful change in prevailing research direction. Consideration and movement towards addressing all of these IPM-related issues will keep New Zealand's agricultural enterprises competitive with the rest of the world.

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