Session 8：Residual Insecticides

Residual insecticides in stored product arthropods: anything amiss?

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Abstract

In the 75 years since the onset of synthetic insecticide use and some 52 years since *Silent Spring* reported on its problems, the management of stored product insects has largely depended on insecticides, particularly residual insecticides. This dependence lingers despite the myriad control alternatives developed throughout the years. Residual insecticides are broadly used for stored product protection, either to complement fumigation and protect against reinfestations or to altogether replace fumigation when its use is ineffective (e.g., in the absence of air-tight conditions). Regardless, insecticide-testing methods in stored product protection rely on acute mortality determinations through time, and population-level assessments are common. In contrast, individual-level assessments are frequently neglected, although this trend seems to be shifting, with more studies of behavior and its consequences for insecticide efficacy. Furthermore, the focus of attention is on direct effects of residual insecticides (e.g., mortality, progeny production) on a single species under exposure. Indirect insecticide effects compromising food sources and non-target arthropods have yet to be targets of attention. The co-occurrence of arthropod species in stored products is also neglected when residual insecticides are used, although such use may interfere with the relative dominance of species sharing this same niche. Eventual shifts in species dominance under insecticide exposure and sublethal effects of insecticides may result in pest resurgence and/or outbreaks, which have yet to be assessed in stored product insects. Translating laboratory experiments to more realistic scenarios while simultaneously considering sublethal effects and multiple species occurrence is also a challenge deserving of overdue attention. A final point of note is the currently fashionable use of bioinsecticides, particularly botanicals, which still share the same potential risks of synthetic insecticides when similarly used because the toxicological characteristics of a given compound are determined by its structure (and related physiochemical properties), and not its origin, be it synthetic or natural.

Keywords: ecotoxicology, indirect effects, sublethal responses, dominance shift, hormesis

1. Insecticides, Residual Insecticides and Stored Products

God, who is inordinately fond of beetles (grain borers and weevils included), would have invited an insecticide industry representative on the 8th day after concluding the creation of the world and said “I changed my mind about insects!” This portrait by the British novelist John Brunner (*The Sheep Look Up*; Haper & Row, 1972) allows a glimpse into the perceived efficacy and potential impact of insecticides by a layperson. In truth, insecticides represent an interesting paradox where, in spite of the serious human safety and environmental concerns that these compounds elicit, their worldwide use remains on the increase (Pimentel, 2005; Ghimire and Woodward, 2013; Oliveira et al., 2014).

Insecticides, as commonly perceived in Stored Product Protection, encompass residual insecticides (also referred to as protectants, contact insecticides, or conventional insecticides) and fumigants (i.e., an insecticide that under normal temperature and pressure conditions exists as gas, or more simply, an insecticidal gas). Residual insecticides are the focus of our discussion and are indeed broadly used for stored product protection to prevent insect infestation with structural treatments and/or to complement fumigation by protecting against reinfestations or to altogether replace fumigation when their use is ineffective (e.g., when lacking air-tight conditions). Therefore, the use of residual insecticides is frequent and important particularly in warmer climates, where insect infestations in stored products are severe and occur throughout the year.

Research on alternative methods for managing stored product insects has been bloomed over recent years with varied possibilities (Subramanyam and Hagstrum, 2000; Phillips and Throne, 2010). Curiously though, residual insecticides prevail in stored product protection despite their inherent risks to human and animal health. Reasons for their continued use are rather diverse, but high efficacy, fast activity, residual protection (i.e., protection through time), relative simplicity of use and low cost are in the forefront. Even more curious, there is little reason to think that the prevalence of residual insecticide use will change anytime soon, given the general trend observed in global insecticide use (Cooper ad Dobson, 2007; Sexton et al., 2007; Ghimire and Woodward, 2013).

The requirements for residual insecticides in stored products are rather restrictive and include high efficacy against stored product insect pests and great safety to humans and domestic animals, in addition to prolonged residual activity with a few months of protection, no product quality interference, ease of handling and affordability. It is no wonder that few conventional insecticides are approved for such use, and those that are mainly include a few organophosphates of old (chlorpyrifos-methyl and pirimiphos-methyl) and pyrethroids. Insect growth regulators, such as methoprene, have also been used as well as pyrethrins, chlorfenapyr, and spinosad, the latter a more recent addition to the list. Spores of *Bacillus thuringiensis* are also used against stored product moths, and botanical insecticides have been the targets of burgeoning attention in recent years.

The novel insecticidal compounds currently in use, such as spinosad and botanicals [the latter much researched but limited to small-scale use (Isman and Grieneisen, 2014)], brought stored product protection into the realm of largely unnecessary semantics, leading to the coinage of exuberant and appealing nomenclature, such biorational insecticides, bioinsecticides, and reduced-risk pesticides, among others. The concern is basically the pitfall of such references, which may convey the equivocated notion that compounds of natural origin (frequently referred as biorational or bioinsecticides) are safe, neglecting the fact that it is the chemical structure and its related physicochemical properties that determine toxicity, not the origin (natural or synthetic).

"Reduced-risk pesticide" is another neologism, as well as a misnomer, because it is an increasingly utilized, newly coined term, but its use is questionable and misleads public perception. The term refers to pesticides exhibiting at least one (and not necessarily more) of the following six advantageous traits over existing pesticides: 1) lower impact to human health; 2) lower toxicity to non-target organisms; 3) lower potential for groundwater contamination; 4) lower use rates; 5) lower pest resistance potential; and 6) higher compatibility with Integrated Pest Management. Therefore, the concept of a reduced-risk pesticide is not stringent and is likely to describe most of the compounds developed since the 1970s, even if they are not selective and exhibit a high potential for promoting insecticide resistance. Therefore, the potential non-target impact of the aforementioned reduced-risk pesticides, including those aimed at stored product protection, should not be neglected.

2. Residual Insecticides in Stored Product Protection

2.1. Current efforts

Residual insecticides remain a matter of concern in stored product protection. A quick survey of the scientific literature on the subject, based on the *Web of Science* database (Thomson Reuters), provides some interesting illustrative data. A total of 484 papers have been published about insecticides in stored products since the outset of database coverage (i.e., 1945), where nearly 54% address residual insecticides, 29% address fumigants and a little over 17% address botanicals (Fig. 1a). Since the last International Working Conference on Stored Product Protection, which took place in Estoril (Portugal) in 2010, 230 papers were published on the subject, therefore representing nearly half (precisely 47.52%) of the papers published about insecticides in stored products since 1945! The relative amount of papers published on residual insecticides decreased to 44.35%, but publications on fumigants and botanicals increased to 34.78% and 20.87%, respectively (Fig. 1b).

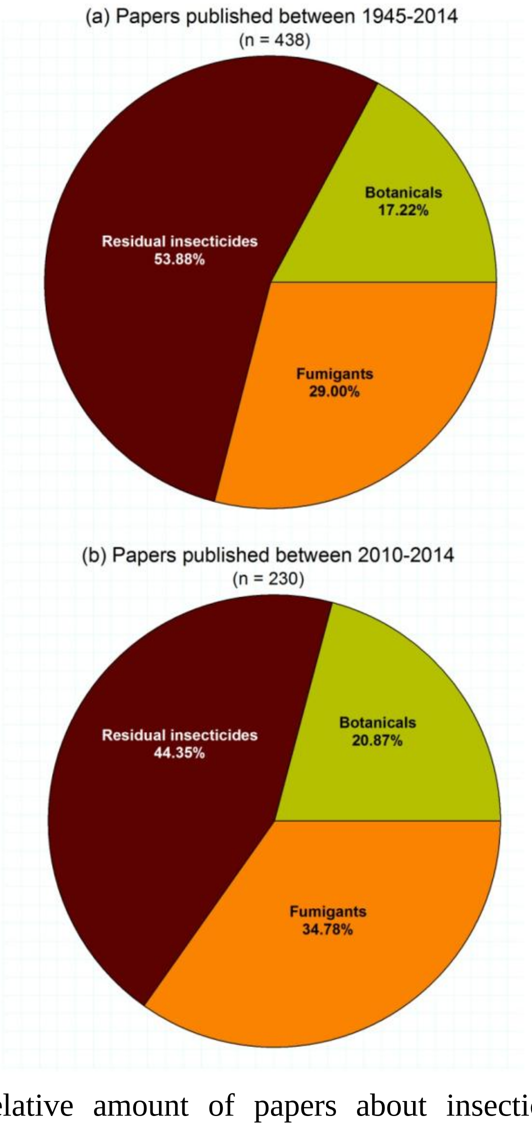

Figure 1 Number and relative amount of papers about insecticides in stored products published in scientific journals between1945-2014 (a) and 2010-2014 (b). The data were obtained from the *Web of Science* database (Thomson Reuters).

The publication data obtained reinforce the perception of the importance of residual insecticides to stored product protection, although fumigants and botanicals exhibited an increase in attention. The phasing out of methyl bromide and the search for alternatives to this fumigant explain the increase in attention to fumigant research in recent years. The increase in attention drawn by botanicals, in contrast, is a likely result of changes in society's attitude and perception towards conventional (synthetic) pesticides, in general demanding compounds with better safety profiles. As the notion of the greater safety of natural compounds permeates the perception of the general public, albeit mistakenly, research on the potential use of botanicals is also on the increase, which has been the case since the initial interest sparked by neem insecticides in the 1980s (Isman and Grieneisen, 2014).

Scrutiny of the papers published on residual insecticides in stored products affords another noteworthy piece of information. Approximately 90% of the studies published about insecticides in stored products since 1945 are efficacy studies, and most of them focus on lethal short-term effects. The trend, however, seems to have shifted in recent years (i.e., the last four years), and the number of efficacy studies with residual insecticides is more evenly matched with alternative ecotoxicology studies ranging from delayed-toxicity to sub-lethal studies and insecticide resistance, among other topics. This new trend is likely a reflex to the editorial positions of key scientific journals restricting acceptance of pure efficacy studies and favoring more comprehensive approaches.

General insecticide efficacy tests focus mainly on mortality as the end result, and this is particularly true for field pests (Stark and Banks, 2003). In contrast, time and progeny production are frequent concerns in insecticide efficacy tests against stored-product insects, which is easily noticeable in studies of residual insecticides (White and Leesch, 1996; Zettler and Arthur, 2000; Obeng-Ofori, 2010). In such cases, the residual effects of an insecticide on the population size are usually considered because residual protection is paramount in stored products protection (Guedes et al., 2011). There is no denying the importance of mortality assessments, but the emphasis in stored-product protection with residual insecticides is better attuned with the ecotoxicological approach to insecticide studies, where population-based assessments are the focus of attention (Forbes and Calow, 1999; Stark and Banks, 2003).

The time-population size assessments used in stored products are important because population size is determined not only by death but also by birth, immigration and emigration of individuals. Furthermore, each new birth has the innate potential of giving birth after reaching sexual maturity, thereby contributing to population size. Population size by itself, with its change over time, is a determinant of population growth dynamics. Efficacy studies on stored products seem to reflect at least some of these concerns, unlike most of the efficacy studies in field pest species, which seems to maintain a certain level of appeal for them, allowing their publication in scientific journals until the present. This, however, seems to be changing.

2.2. Look ahead

Any given insecticide will generally contribute to mortality in a given species and, in doing so, may indirectly affect birth, immigration and emigration in the population, potentially interfering with the population age structure. Nonetheless, an insecticide frequently exhibits secondary effects that directly interfere with birth, immigration and emigration in a given insect population. Moreover, an insecticide can affect availability of valuable resources for insect maintenance and can potentially interfere with its predators, leading to indirect effects on the target species population. In summary, the insecticide-pest interactions may be rather complex, and such complexity may not be reflected in the prevailing research approaches in stored product protection.

Efficacy studies ultimately allow estimation of eventual recommended label rates of insecticides, and, again, this is usually established based on the direct mortality caused by an insecticide on the target species, or at least its potential to quickly reduce the pest population. Residual efficacy assessment is no different, but considers such results through extended periods of time (a few months). A shortcoming is that natural breakdown or even non-uniform insecticide application leads to sub-lethal doses of insecticide reaching the targeted species population. Such insects can also exhibit (genetic) variation in their insecticide susceptibility, and their response to insecticide exposure through time will differ. Therefore, sublethal insecticide toxicity should be a target of attention when dealing with residual insecticides, but it is frequently neglected in efficacy studies. A previously published survey of 26 studies on the sublethal effects of insecticides in 11 species of stored-product insects provides support for the stated contention (Hagstrum and Subramanyam, 2006).

Current studies on residual insecticides focus on a single pest species and usually explore direct (lethal) effects on the targeted species, as previously mentioned. However, although the stored product environment is rather artificial and greatly simplified, this environment is co-habited by several different pest species and their natural enemies, not to mention detritivorous species (e.g., fungi). Individuals of a given species are affected by their conspecifics and by heterospecifics, which can all be affected by insecticide exposure both at lethal and sublethal levels. These effects can be significant, but are rarely tested. In that regard, a recent study exploring insecticide effects on co-occurring stored product insect species is worth mentioning to illustrate the case.

The maize weevil *Sitophilus zeamais* and the lesser grain borer *Rhyzopertha dominica* exhibit common co-occurrence in stored cereals in warmer climates. In stored maize, for instance, the maize weevil usually prevails in larger populations in tropical conditions, even though the lesser grain borer is also commonly found in the same grain mass. This ecological dominance of the weevil over the borer changes with insecticide exposure, following predictions consistent with the intermediate disturbance hypothesis (Cordeiro et al., 2014). This hypothesis predicts that intermediate levels of disturbance will maximize species diversity while reducing the proportional abundance of competitively dominant species (Connell, 1978; Shea et al., 2004). Based on this hypothesis, high insecticide disturbance, due to high insecticide doses and/or rates of application, are likely to suppress one, if not both, competing beetle species, while very low doses and/or rates of application should not affect these species. However, at intermediate doses and/or rates of application, the prevalence of the dominant species may be compromised if it is more susceptible to the compound used. Indeed, fenitrothion-sprayed maize grains at 0.70 ppm were able to shift the ecological dominance from *S. zeamais* to *R. dominica,* which became the most prevalent species, as illustrated in Figure 2 (Cordeiro et al., 2014).

Another relevant issue to consider in stored product protection with residual insecticides is the potential for interactive effects of mixed compounds. Although the application of a single insecticide usually prevails in residual insecticide testing, the use of insecticide mixtures seems to be increasing, and in some countries, such as Brazil, technical recommendations for the use of insecticide mixtures prevail. The Brazilian popular rationale is that the local populations of the maize weevil are usually resistant to pyrethroids, but susceptible to organophosphates (Pereira et al., 2009). In contrast, Brazilian populations of the lesser grain borer are more frequently resistant to organophosphates rather than to pyrethroids (Guedes et al., 1996). Therefore, the simultaneous use of an organophosphate (either fenitrothion or pirimiphos-methyl) with a pyrethroid (bifenthrin or deltamethrin, for instance) allows effective control of both species. However, simultaneous selection for resistance to both compounds may take place, and early indications of that are already discernible (Corrêa et al., 2011). Additionally, synergistic use may hold a greater potential for insecticide resistance management in such a case, and cross-contamination with insecticides and fungicides (even from field applied fungicides), for instance, may have relevant consequences for stored product protection, possibility largely neglected so far.

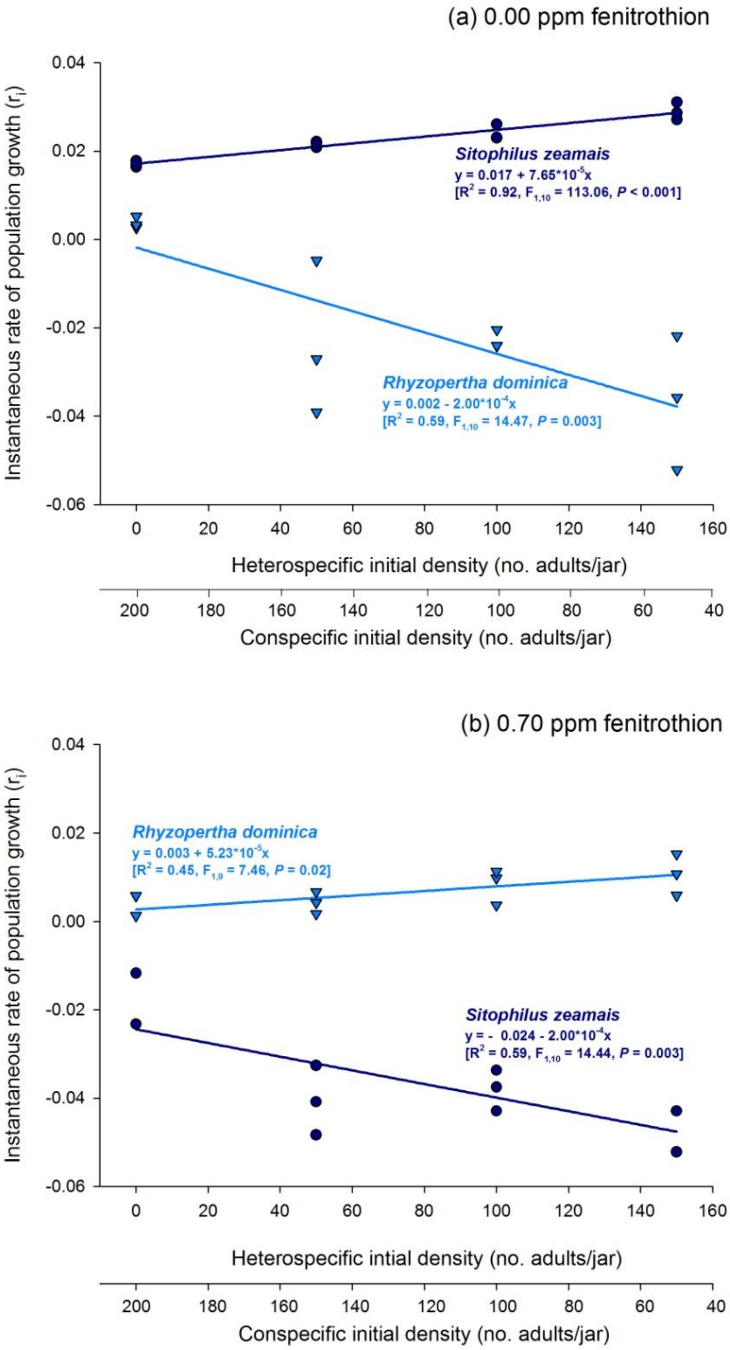

Figure 2 Effect of heterospecific density on the population growth of two competing species of stored grain beetles (*Sitophilus zeamais* and *Rhyzopertha dominica*) reared on maize grains either free of insecticide residue (a) or contaminated with 0.70 ppm fenitrothion (b). [Adapted from: Cordeiro et al. (2014)]

3. Challenges of Residual Insecticide Research

The portfolio expansion of residual insecticides for use in stored product protection is a current necessity due to, among other things, the emergence of resistance to the insecticides currently being used and the availability of alternative compounds with a better price, field performance and/or user safety. However, the testing of such compounds should not be restricted to acute mortality assessments, even through time. More comprehensive assessments, including sublethal effects, should be considered. Readily noticeable behavioral patterns have already been reported in stored product insects, and they may play pivotal roles in insecticide efficacy. An example with psocids demonstrates this; walking activity may differ between species, and higher activity is likely to favor insecticide exposure via treated surfaces, as reported for *Liposcelis entomophila* compared with *L. bostrychophila*, favoring survival of the latter, which is also affected by the insecticide (Fig. 3) (Guedes et al., 2008).

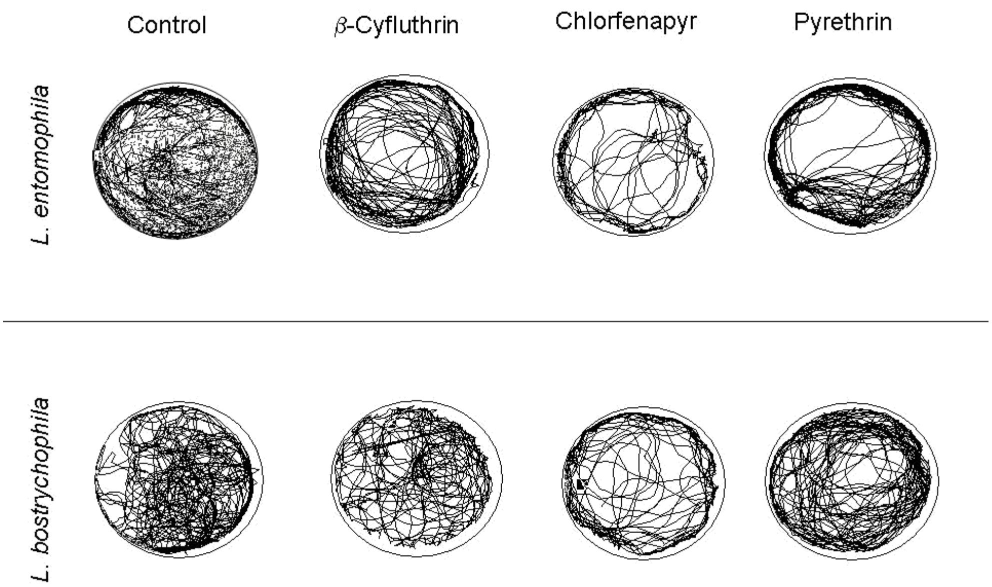

Figure 3 Representative tracks showing the walking activity of individual psocids from two species (*Isosceles bostrychophila* and *L. entomophila*) over a 10 min period on concrete surface arenas (2.5 cm diameter) fully sprayed with either water or insecticides. [Adapted from: Guedes et al. (2008)]

Perhaps even more interesting is the fact that population differences in behavior may also contribute to lower insecticide efficacy. Variation in stimulus-dependent behavioral avoidance have been detected among populations of *S. zeamais*, with some cases of (physiologically) resistant populations also exhibiting behavioral avoidance to the same insecticide or to a different one, which only adds complexity to the management of such populations (Guedes et al., 2009a,b; Braga et al., 2011). However, only considering population differences in behavioral responses may be a mistake because behavioral variability may prevail at the individual level, given that behavior is an individual trait. Therefore, even within a single population, enough behavioral variability may exist to allow adequate survival of individual insects for eventual reinfestation. This notion is another that has not yet been fully tested, with just a single recorded attempt (Morales et al., 2013).

In addition to behavior, life history traits may also be affected by sublethal insecticide doses, leading to phenomena such as insecticide-induced hormesis. This phenomenon refers to beneficial (stimulatory) effects associated with toxic compounds (e.g., insecticides) at higher doses (Guedes and Cutler, 2014). The phenomenon provides biphasic, dose-response relationships and is little studied among insects and mites, although it has been recognized and is well-documented in several instances and is likely to be a rule rather than an exception in pesticide-arthropod interactions (Cutler, 2013; Guedes and Cutler, 2014). This phenomenon has been recognized as a potential cause of pest resurgence and secondary pest outbreaks (Hardin et al., 1995; Cordeiro et al., 2013), which is reason enough for attention. However, the phenomenon has also been detected in stored product insects and, worse yet, insecticide resistant populations may exhibit higher potential population increases when exposed to low, sublethal insecticide doses than do susceptible insects (Guedes et al., 2010; Guedes and Cutler, 2014; Vilca Mallqui et al., 2014). This fact creates additional concerns regarding the management of stored product insects, and of insecticide resistant populations of these species in particular because insecticide field rates may not provide control against resistant populations and may actually boost their populations, with consequent increase (and perhaps spread) of insecticide resistant alleles (Guedes et al., 2010, 2011).

Another curious omission in stored product protection is the secondary (cross) exposure that likely occurs between insecticides used in the field and those used in storage. An insecticide sprayed in the field on grains before harvest may affect stored grain insects that infest before harvest, a relatively frequent phenomenon in warmer climates that occurs with weevils and *Plodia interpunctella*, the Indian meal moth. Therefore, field-applied insecticides may select some stored product insects for resistance while still in the field, carrying the effect into stores and potentially compromising the use of field-class insecticides in stored product protection. A case such as this seems to have taken place in Brazilian populations of exposed to indoxacarb, a sodium channel blocker used for caterpillar control in maize fields (Haddi et al., 2015). Another possibility in need of scrutiny is the selection for resistance to *Bacillus thuringiensis* δ-endotoxins due to the large-scale use of genetically modified maize cultivars, which may select stored grain moths for resistance both in the field and later in storage. It is worth remembering that the Indian meal moth exhibited the first case of Bt resistance among insects in the mid-1985 (McGaughey et al., 1985). The reemergence of the Angoumois grain moth as a species that frequently infests Brazilian stores of transgenic maize also seems to lend credence to the possibility of inadvertent selection for Bt resistance in populations of this pest species.

A matter of concern regarding the experimental evidences emphasized above is that they were obtained in laboratory settings. The research discussed above provides important evidence for potentially serious concerns, but field studies are lacking. Transposing the laboratory studies into more realistic scenarios, allowing more definitive assessments of the risks involved, is a great challenge and remains to be done. Regular efficacy testing has been successfully transferred to stored product settings, but the same should take place for more comprehensive ecotoxicological assessments, a challenge yet to be successfully faced.

4. Conclusions

The published literature in stored-product protection with residual insecticides is replete with information on lethal (direct) effects of insecticides in insect pests. These studies are important; however, they are limited by a lack of consideration of sublethal and indirect insecticide effects, which may result in problems with pest resurgence, secondary pest outbreaks and enhance current difficulties in managing insecticide resistant populations. As residual insecticides remain important components of stored product protection and are likely to remain so, more comprehensive studies on insect-insecticide interactions are necessary and are already in demand. An early perception stated by Rachel Carson in reference to entomology and insecticides, but projected into the future and applied to stored product protection, highlights the penalty of not recognizing the above mentioned needs and challenges: "*It is our alarming misfortune that so primitive a science has armed itself with the most modern and terrible weapons* (*Silent Spring*, Houghton Mifflin, 1962)."

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