

Opportunities for Integrated Pest Management to control the Poultry Red Mite, *Dermanyssus gallinae*

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Summary

Dermanyssus gallinae is the most economically important ectoparasite of laying hens in Europe. Control of *D. gallinae* is already hampered by issues of pesticide resistance and product withdrawal and, with the prohibition of conventional cages in 2012 and the resulting switch to more structurally complex housing which favours red mite, the importance of managing this pest will increase. Integrated Pest Management (IPM), as often employed in agricultural pest control, may be a way to address these issues where a combination of different novel control methods could be used with/without conventional management techniques to provide a synergistic and more efficacious effect. Work at Newcastle has shown that essential oils including thyme and garlic may act as effective *D. gallinae* repellents and acaricides, whilst preliminary vaccine studies have demonstrated a significant increase in mite mortality *in vitro* using concealed antigens. Work elsewhere has considered predators and fungi for *D. gallinae* control and other husbandry techniques such as manipulating temperature and lighting regimes in poultry units. This paper will review the available and emerging techniques for *D. gallinae* control and discuss which techniques might be suitable for inclusion in an integrated management programme (e.g. synthetic acaricides and diatomaceous earths).

Keywords: *Dermanyssus gallinae*; integrated pest management; control

Introduction

The poultry red mite, *Dermanyssus gallinae*, is currently the most economically deleterious ectoparasite of laying hens in Europe (Chauve, 1998). Research has shown that in the UK between 60% (Fiddes et al., 2005) and 85% (Guy et al., 2004) of commercial egg-laying premises may be infected with *D. gallinae*, with higher mite populations typically seen in free range systems compared to cage units (Guy et al., 2004; Fiddes et al., 2005). This is of particular concern given that conventional cages will be prohibited in the EU from 2012 under EU Directive 99/74/EEC and thus the proportion of hens housed in alternative systems such as free-range is likely to increase substantially. *D. gallinae* prevalence in laying flocks worldwide may vary even more than that reported for the UK, from 20 to 90% depending upon the country and production system considered (Sparagano et al., 2009). Evidence for higher infestation rates in free-range systems also appears to be country-dependant on a global scale, and factors such as flock/farm size may also be important in governing infestation rates (Sparagano et al., 2009).

D. gallinae feeds on blood, preferring to feed from birds for a brief period every few days during periods of darkness, while the majority of their life-cycle is spent off the host. Populations of *D. gallinae* are capable of rapid expansion under the amenable conditions found in most poultry houses, where Axtell (1999) observed that complete development from egg to adult can occur in as little as two weeks. The turnover of hens in laying systems typically exceeds 70 weeks, allowing ample time for *D. gallinae* populations to proliferate (Höglund et al., 1995). Where infestations of *D. gallinae* are sufficiently severe, mite feeding may result in significant stress to hens with subsequent declines in bird condition, growth rates, egg quality (through increased shell thinning and spotting) and egg production (Chauve, 1998). In extreme cases, *D. gallinae* population levels may be so high that anaemia, and even death of hens can result (Wojcik et al., 2000; Cosoroaba, 2001). It has also been reported that *D. gallinae* may serve as a vector for poultry pathogens and possible zoonoses such as *Salmonella* spp. (reviewed by Valiente Moro et al., 2009), suggesting a potential risk to human health.

Economic costs associated with both control and production losses due to *D. gallinae* have been estimated at €130 million annually for the EU egg industry (van Emous, 2005), where control of *D. gallinae* has typically been achieved by the use of synthetic contact acaricides including carbaryl, diazinon, dichlorvos and permethin. However, the continued use of these products may be hampered by issues of mite resistance (Beugnet et al., 1997; Kim et al., 2004, Fiddes et

al., 2005) and decreasing product availability as a result of tighter legislation regarding their use. Indeed, in Sweden there were no registered compounds available for the control of ectoparasites at the start of the last decade (Chirico and Tauson, 2002). Management of *D. gallinae* by conventional acaricides is further hampered by the behaviour of this pest. When not obtaining a blood meal, mites retreat to small cracks and crevices within the poultry housing system, where they are effectively protected from any acaricide that exerts its effect through contact toxicity. With increasing reports of *D. gallinae* resistance to synthetic acaricides and changes in legislation and production practises, it is likely that in the future many more of the world's 2.8 billion laying hens (11.7% of which are located in the EU) (Axtell, 1999) will suffer as a result of *D. gallinae* infestation. With this in mind, it is important to identify and evaluate new approaches for the management of *D. gallinae* in poultry systems. Research in the areas of novel acaricides, immunological control, biological control and animal/premise husbandry are all areas in which research is being undertaken in an attempt to control *D. gallinae*. Whilst promising results have been reported in all these areas, work to combine management techniques in an integrated approach to *D. gallinae* control remains wanting. Research focusing on crop pests suggests that such an Integrated Pest Management (IPM) approach which combines control strategies can have numerous benefits over conventional control (i.e. the use of synthetic pesticides alone) (Dent, 1995).

The aim of this paper was to review the main alternatives to synthetic *D. gallinae* control currently being researched and developed and to assess if these would lend themselves to combination with one-another, as well as conventional synthetic acaricides, to achieve an integrated approach to *D. gallinae* management.

Novel acaricides

Bio-pesticides

Bio-pesticides can comprise either bacterial endotoxins or the bacteria themselves. The bacteria *Bacillus thuringiensis* with known pathogenicity in insects has been shown to produce mortality in ticks (Hassanain et al., 1997) and has been used for the control of mites of agricultural crops (van der Geest et al., 2000; Dolinski and Lacey, 2007).

Biological insect toxins are now commonly used as crop sprays and have even been incorporated into crop plants via genetic engineering, with *B. thuringiensis* (*Bt*) and *Bt* maize being undoubtedly the best-known examples. Spinosad, a natural product derived from fermentation of the micro-organism *Saccharopolyspora spinosa*, is another such

biopesticide that has been used successfully against a range of insect pests, with corresponding research also finding that this product possesses relatively low toxicity to mammals and birds with 70-90% of beneficial insects also left unharmed by exposure (Anastas et al., 1999). Although the toxicity of spinosad to mites *per se* has been reported as being variable and/or reduced in comparison to insect species (Villanueva and Walgenbach, 2006; Holt et al., 2006), experiments using this product against the ectoparasitic cattle tick *Boophilus microplus* have produced some promising results, although repeat applications might be necessary according to the work conducted (Davey et al., 2001, 2005). Pathogenic bacteria of arthropods could provide an alternative means of mite control. This suggests that spinosad, along with other 'new-generation' bio-pesticides, may warrant investigation as premise sprays to manage *D. gallinae* populations.

Inert dusts

Inert dusts primarily include diatomaceous earths containing silica (although synthetic amorphous silica-based products also exist). They absorb lipids from the epicuticle of the exoskeleton of pest invertebrates, effectively resulting in death by dehydration. Whilst inert dusts have been well studied for their pesticidal potential and may provide an attractive alternative to synthetic chemicals for pest control, work with these products for use against *D. gallinae* has shown that; "... the quality of the raw material is the dominant factor for the effectiveness of DE [diatomaceous earth] products" (Maurer and Perler, 2006). There is therefore a need to evaluate the efficacy of inert dusts under laboratory conditions to ascertain which specific products are likely to have the greatest benefit in *D. gallinae* management. Work by Kilpinen and Steenberg (2009) evaluated a range of commercial inert dusts against *D. gallinae* under laboratory conditions and similarly reported variation in efficacy depending upon the product used, as well as with variations in humidity. High humidity levels (>85%) were shown to reduce the efficacy of inert dust products, suggesting that if used in poultry units with such high humidity levels, measures such as increased application rates would be necessary.

Plant-derived products

Plant-derived products may offer an alternative to synthetic acaricides for managing *D. gallinae* populations and recent research in this field has produced some promising results (Kim et al., 2004, 2007; Lundh et al., 2005; George et al., 2009a; Maurer et al., 2009). Several pesticides based on plant constituents are already used widely in certain areas

of pest management (Isman 2006), including against pests of veterinary significance (George et al., 2008). Products based on extracts from the neem tree (particularly its seeds), for example, are commonly employed in pest management *per se*. Neem oil has been reported to have biocidal effects against some 200 species of arthropod pests (Choi et al., 2004), including ticks (Pathak et al., 2004) and *D. gallinae* (Lundh et al., 2005). Preliminary work by Kim et al. (2004) tested 56 plant essential oils for their acaricidal effect on *D. gallinae*. Of these, oils from bay, cade, cinnamon, clove bud, coriander, horseradish, lime dis 5F, mustard, pennyroyal, pimento berry, spearmint and thyme all gave 100% mite mortality in contact toxicity tests at a concentration of 0.07 mg of oil per cm². Further experiments by Kim et al. (2004) showed that the acaricidal effect of selected essential oils was attributable to action in the vapour phase, an observation supported in later work from the same group (Kim et al., 2007). In similar work by George et al. (2009a), 50 plant essential oils were assessed for their toxic effect on *D. gallinae*. Twenty of the essential oils chosen gave greater than 80% mite mortality over 24 hours when used at a concentration of 0.14mg/cm³, with 1 in every 5 of the 50 essential oils used, including thyme, tea tree and garlic, giving 100% mortality.

Vaccines

Vaccines provide attractive alternatives to insecticides for the same reasons as they are preferable to antibiotics, including lack of residues in foodstuffs, no withdrawal periods, no environmental contamination, avoidance of resistance in target populations and ease of administration (Shryock, 2004). Until recently, there were few reports in the literature detailing the development of a *D. gallinae* vaccine or prospective vaccine candidates.

Immunisation of birds with somatic *D. gallinae* antigens has met with variable success. Arkle et al. (2009) found no significant difference in *D. gallinae* mortality when fed *in vitro* on blood from birds immunised with *D. gallinae* proteins and controls. However, both Wright et al. (2009) and Harrington et al. (2009a) reported a significant 7.5% or 50.6%, respectively, increase in *in vitro* mite mortality when fed blood spiked with egg-extracted antibodies from *D. gallinae* immunised birds. However, both authors used different methods of protein extraction; Harrington et al. (2009a) used a urea-based method, whilst Wright et al. (2009) identified significant mite mortality using PBS-extracted proteins but reported no significant effect of urea-extracted *D. gallinae* proteins on mite mortality. A genomics approach has also been undertaken to investigate *D. gallinae* vaccine candidates. Bartley et al. (2009) identified an orthologue of tick histamine release factor (HRF) in *D. gallinae* and suggested the protein could have a regulatory

function in mites. Following production of the recombinant protein *Dg*-HRF-1, *in vitro* testing against *D. gallinae* demonstrated a significant 7% increase in mite mortality compared to controls. Harrington et al. (2009b) immunised laying hens with recombinant proteins derived from ticks (Bm86) or mosquitos (subolesin). Bm86 has well documented activity against *Boophilus microplus* (reviewed by de la Fuente et al. 2007), although non-*Boophilus* spp. activity is variable (Willadsen, 2004), whilst subolesin has been shown to be highly conserved across a number of arthropods, including ticks, and can affect blood meal digestion and reproduction in ticks (de la Fuente et al, 2006; Kocan et al., 2007). Harrington et al. (2009b) demonstrated a significant 35.1% increase in *D. gallinae* mortality in subolesin-immunised versus control birds in an *in vitro* assay, whilst immunisation with Bm86 resulted in a non-significant, but numerical 23% increase in mite mortality.

The development of arthropod vaccines is notoriously difficult due to the limiting step of identification and characterisation of new protective antigens, and this has restricted the availability of commercial vaccines against arthropod ectoparasites (reviewed by Willadsen, 2004). The recent research on *D. gallinae* antigens has demonstrated that there is potential to develop a vaccine to control the poultry red mite. However, the approaches undertaken have so far relied upon the concealed antigen approach, whereby the host immune system is not normally exposed to mite antigens, for example gut epithelial cell, and as such the parasite has not developed host-immune avoidance mechanisms. This approach is not without pitfalls, most notably the necessity to repeatedly vaccinate animals due to the lack of stimulation of host immunity by these concealed antigens.

Biological control

Natural enemies

Natural enemies in the form of predators and parasitoids can be of great benefit in controlling crop pests (Gurr et al., 2004). Where naturally occurring populations are insufficient to provide pest management benefits, mass releases of artificially reared individuals can be used to reduce pest populations. Such releases are especially effective in enclosed systems (such as greenhouses), where the natural enemies are confined to the release site and so must necessarily feed/parasitize the target pest in order to survive. Whilst little work has been done to assess the potential of predators and parasitoids to control *D. gallinae* populations, the fact that hens are typically housed in at least partly

enclosed systems suggests that such control might be achievable if suitable candidates are identified for mass rearing and release.

Work has been done to suggest that suitable candidate predators may exist for use against *D. gallinae* in poultry systems. Numerous authors have reported the occurrence of the predatory mite *Cheyletus eruditus* in poultry houses where this species has been observed feeding on juvenile *D. gallinae* (Lesna et al., 2009). Releases of *C. eruditus* have not provided control of *D. gallinae* in experiments to date, although additional research has identified a further two predatory mite species (*Hypoaspis aculeifer* and *Androlaelaps casalis*) with *D. gallinae* management potential (Lesna et al., 2009). It is possible that other predatory species aside from mites would also prey upon *D. gallinae*, although mass-rearing and release of species such as predatory beetles would be more difficult to achieve. Similarly, whilst parasitoids are often mentioned with regard to crop pest control, many of these species (such as the parasitic Hymenoptera) require additional resources to survive and reproduce (such as pollen and nectar) that would not be present within a poultry unit.

Entomopathogenic fungi

Entomopathogenic fungi are currently used worldwide for control of a wide range of arthropod pests, particularly pests in protected crops or field crops. *D. gallinae* has been found to be susceptible to infection by isolates of each of the species *Beauveria bassiana*, *Metarhizium anisopliae* and *Paecilomyces fumosoroseus* when mites were inoculated with high doses of conidia (Steenberg and Kilpinen, 2003). In subsequent work on the same project isolates from *B. bassiana* consistently proved to be most virulent and persistent over time, with up to 80% transmission when 5% of mites had been treated (Steenberg et al., 2006). Nevertheless, semi-field experiments showed that although the fungus was capable of reducing *D. gallinae* population growth, control levels were not satisfactory (Steenberg et al., 2006). This probably results from the fact that the time required to kill *D. gallinae* was sufficiently long to allow females to oviposit, where treatment was reported not to have effected oviposition (Steenberg et al., 2006). Use of entomopathogenic fungi may also be dependant on maintaining adequate humidity levels to ensure fungal transmission and it remains to be seen if this method can be successfully developed and employed in the field for *D. gallinae* control.

Bacterial endosymbionts

In blood feeding arthropods, endosymbiotic bacteria are often essential for the full digestion of the blood meal, especially if the arthropod relies solely on the blood meal (Lehane, 2005). Bacteria from the genus *Wolbachia* spp., *Cardinium* spp., and *Spiroplasma* spp., have been widely reported to be associated with arthropods whilst infection of hosts with *Wolbachia* spp. or *Cardinium* spp. has been associated with cytoplasmic incompatibility between infected and uninfected individuals and disturbance of oogenesis (Hunter et al., 2003; Gotoh et al., 2007). Both *Spiroplasma* spp. and *Cardinium* spp. have been identified in *D. gallinae* (de Luna et al., 2009; Valiente Moro et al. 2009b), although currently *Wolbachia* spp. have still not been found in mites. The use of endosymbiont bacteria in *D. gallinae* control is an interesting concept, either perhaps via the use of bacteria to modify the host directly, for example disruption of host oogenesis, or disruption of bacteria involved in digestion of the blood meal.

Animal/premise husbandry

Higher mite populations are typically seen in free range systems compared to cage units (Guy et al., 2004; Fiddes et al., 2005; Arkle et al., 2006) probably as these systems provide both a more favourable habitat for the mites and a greater challenge for decontamination between flocks. Such systems often contain a large number of sites highly suited as *D. gallinae* refugia. When not obtaining a blood meal, mites retreat to these small cracks and crevices where they can easily survive unfed for many months in areas that are difficult to clean down between flocks. It should be possible to design poultry facilities that are less 'mite-friendly' than is currently the norm, although removing all refugia is clearly unrealistic. Recent research suggests that using a Hazard Analysis and Critical Control Point method (HACCP) can be potentially beneficial in preventing *D. gallinae* establishment in all types of hen housing where Mul and Koenraadt (2009) have adapted this technique from that first development by NASA in the 1960s. Forty-one potential infestation hazards are cited, such as introduction and spread of mites by birds, rodents and employees, with suggested corrective actions to minimise *D. gallinae* population establishment. The system has been trialled in Holland and the UK and described as a useful and feasible management tool by poultry farmers.

Mul and Koenraadt (2009) also note the potential of temperature manipulation to control *D. gallinae*, where heating the house between flocks to 55°C is suggested as a control measure. *D. gallinae* population development is known to be temperature dependant, where research suggests that the stage-specific survival of immature mites decreases rapidly outside the range of 10-37°C (Maurer and Baumgärtner, 1992). Tucci et al. (2008) similarly reported high mortality of *D. gallinae* at 35°C indicating that this temperature had adverse effects on mite development. Complete mortality of *D. gallinae* can be expected at greater than 45°C and below -20°C (Nordenfors et al., 1999). This suggests that temperatures of 55°C, which would be expensive to reach and maintain for any length of time, may be excessive for controlling *D. gallinae* and that similar levels of control might be achievable at a reduced temperature (although this might need to be maintained for longer).

It may also be possible to control *D. gallinae* populations by manipulating lighting regimes within poultry units. Research suggests that short-cycle intermittent lighting regimes can markedly reduce *D. gallinae* numbers compared with more standard regimes, although lighting intensity (Zoons et al., 2004; Stafford et al., 2006). This is likely caused by disruption to the mites' normal nocturnal feeding behaviour, although exact reasons remain unclear. However, current EU legislation on hen welfare requires a statutory 8 hour dark period, making it difficult to envisage how intermittent lighting regimes could be employed in practise for *D. gallinae* control.

IPM potential for *Dermanyssus gallinae* control

Many of the different *D. gallinae* management approaches previously described would be amenable to use alongside one-another, as well as in combination with conventional currently used hygiene and chemical control methods. It is likely, for example, that a *D. gallinae* vaccine could, and depending upon the antigen it might be preferable, to use in conjunction with any other control method described. Similarly, the use of novel pesticides would unlikely be unaffected by advances in animal/premise husbandry techniques and *visa versa*, with both being compatible with conventional *D. gallinae* control. Nevertheless, such compatibility would not be true of all the *D. gallinae* control methods described.

Novel pesticides may be just as toxic to invertebrate natural enemies as they are to the target pest. Inert dusts work via the invertebrate cuticle and so can be expected to exert a broad-spectrum effect on all invertebrates. Plant essential oils are thought to disrupt binding of invertebrate nerve cord proteins, specifically ^3H -octopamine (according to work done with the American cockroach *Periplaneta Americana*) (Enan et al., 1998). As such, any product giving high levels of mortality in *D. gallinae* might similarly be expected to do so in predators and parasitoids (also possessing an invertebrate-specific octopaminergic nervous system), although some work exists to suggest that toxicity to invertebrates may depend on the species considered (Isman, 2000; George et al., 2009b). Bio-pesticides may be more species specific and amenable to use alongside natural enemy releases. For example, research suggests that predatory invertebrate species may be relatively tolerant to spinosad, although parasitoids are at much greater risk from exposure (Williams et al., 2003). Use of invertebrate-specific bio-pesticides (and inert dusts) is also likely to be amenable with treating *D. gallinae* infestations with entomopathogenic fungi (although it is plausible that dusts could reduce premise humidity levels). The same may not be true for essential oil-based acaricides, however, where these products are often highly fungicidal. Similarly, animal husbandry techniques involving raising premise temperatures to levels lethal to *D. gallinae* between flocks would likely have an adverse effect on any beneficial organisms present making these techniques incompatible with one-another.

Conclusions

It remains to be seen how many of the new and emerging *D. gallinae* management techniques cited herein will be as useful in practice as preliminary results suggest. It also remains to be seen if any synergistic effect could be gained by combining any compatible techniques in an IPM approach to *D. gallinae* control. Even where techniques are amenable to combination with one-another, this will not automatically infer any pest management benefit in using multiple techniques together. In work by Maurer et al. (2009), for example, mortality of *D. gallinae* exposed to a diatomaceous earth was comparable with or without the addition of 2% pyrethrum extract. Whilst beyond the scope of this paper, as an integrated approach to pest management can also encompass the use of 'conventional' acaricides, the development of new synthetic products such as Phoxim (marketed as 'ByeMite®') should not be overlooked when considering IPM for the control of *D. gallinae*.

Although any consideration of IPM for use against *D. gallinae* remains in its infancy, according to pest management research in other areas, developing methods that could be combined in an integrated approach could be beneficial to *D. gallinae* management in the future. With continued research into new technologies and techniques for *D. gallinae* control an IPM approach to control this important poultry pest has the potential to be realised.

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References

- ANASTAS, P., KIRCHCHOFF, M. and WILLIAMSON, T. (1999) Spinosad – a new natural product for insect control. *Green Chemistry*, August 1999: G88.
- ARKLE, S., GUY, J.H. and SPARAGANO, O. (2006) Immunological effects and productivity variation of red mite (*Dermanyssus gallinae*) on laying hens- implication for egg production and quality. *World's Poultry Science Journal* 62: 249-257.
- ARKLE, S., HARRINGTON, D., DE LUNA, C., GEORGE, D., GUY, J. and SPARAGANO, O.A. (2009) Immunological control of poultry red mite: the use of whole mite antigens as a candidate vaccine. *Annals of the New-York Academy of Sciences* 1149: 36-40.
- AXTELL, R.C. (1999) Poultry integrated pest management; status and future. *Integrated Pest Management Reviews* 4: 53-73.
- BARTLEY, K., NISBET, A.J., OFFER, J.E., SPARKS, N.H.C., WRIGHT, H.W. and HUNTLEY, J.F. (2009) Histamine Release Factor from *Dermanyssus gallinae* (De Geer): Characterization and in vitro assessment as a protective antigen. *International Journal for Parasitology* 39: 447-456.
- BEUGNET, F., CHAUVE, C., GAUTHEY, M. and BEERT, L. (1997) Resistance of the red poultry mite to pyrethroids in France. *Veterinary Record* 140: 577-579.
- CHAUVE, C. (1998) The poultry red mite *Dermanyssus gallinae* (De Geer, 1778): current situation and future prospects for control. *Veterinary Parasitology* 79: 239-245.
- CHIRICO, J. and TAUSON, R. (2002) Traps containing acaricides for the control of *Dermanyssus gallinae*. *Veterinary Parasitology* 110: 109-116.
- CHOI, W., LEE, S., PARK, H. and AHN, Y. (2004) Toxicity of plant essential oils to *Tetranychus urticae* (Acari: Tetranychidae) and *Phytoseiulus persimilis* (Acari: Phytoseiidae). *Journal of Economic Entomology* 97:553-558.
- COSOROABA, I. (2001) Massive *Dermanyssus gallinae* invasion in battery-husbandry raised fowls. *Revue De Médecine Vétérinaire* 152: 89-96.
- DAVEY, R.B., GEORGE, J.E. and SNYDER, D.E. (2001) Efficacy of a single whole-body spray treatment of spinosad against *Boophilus microplus* (Acari: Ixodidae) on cattle. *Veterinary Parasitology* 99: 41-52.
- DAVEY, R.B., MILLER, J.A., GEORGE, J.E. and SNYDER, D.E. (2005) Effect of repeated spinosad treatments on cattle against *Boophilus annulatus* under South Texas field conditions. *Southwestern Entomologist* 30: 245-255.
- DE LA FUENTE, J., ALMAZÁN, C., BLAS-MACHADO, U., NARANJO, V., MANGOLD, A.J., BLOUIN, E.F., GORTAZAR, C. and KOCAN, K.M. (2006) The tick protective antigen, 4D8, is a conserved protein involved in modulation of tick blood ingestion and reproduction. *Vaccine* 24: 4082-4095.
- DE LA FUENTE, J., ALMAZÁN, C., CANALES, M., PERÉZ DE LA LASTRA, J.M., KOCAN, K.M. and WILLADSEN, P. (2007) A ten-year review of commercial vaccine performance for control of tick infestations. *Animal Health Research Reviews* 8: 23-28.
- DE LUNA, C., VALIENTE MORO, C., GUY, J.H., ZENNER, L. and SPARAGANO, O.A.E. (2009) Endosymbiotic bacteria living inside the poultry red mite (*Dermanyssus gallinae*). *Experimental and Applied Acarology* 48: 105-113.
- DENT, D. (1995) *Integrated pest management*, pp. 368 (Chapman & Hall).
- DOLINSKI, C. and LACEY, L.A. (2007) Microbial control of arthropod pest of tropical tree fruit. *Neotropical Entomology* 36: 161-179.

- ENAN, E., BEIGLER, M. and KENDE, A. (1998) Insecticidal action of terpenes and phenols to cockroaches: effect on octopamine receptors. Paper presented at the International Symposium on Plant Protection, Gent, Belgium.
- FIDDES, M.D., LE GRESLEY, S., PARSONS, D.G., EPE, C., COLES, G.C. and STAFFORD, K.A. (2005) Prevalence of the poultry red mite (*Dermanyssus gallinae*) in England. *Veterinary Record* 157: 233-235.
- GEORGE, D.R., GUY, J.H., ARKLE, S., HARRINGTON, D., DE LUNA, C., OKELLO, E.J., SHIEL, R.S., PORT, G. and SPARAGANO, O.A.E. (2008) Use of plant-derived products to control arthropods of veterinary importance; a review. *Annals of the New York Academy of Science* 1149: 23-26.
- GEORGE, D.R., SPARAGANO, O.A.E., PORT, G., OKELLO, E., SHIEL, R.S. and GUY, J.H. (2009a) Environmental interactions with the toxicity of plant essential oils to the poultry red mite *Dermanyssus gallinae*. *Medical and Veterinary Entomology*, in press.
- GEORGE, D.R., SPARAGANO, O.A.E., PORT, G., OKELLO, E., SHIEL, R.S. and GUY, J.H. (2009b) Toxicity of plant essential oils to different life stages of poultry red mite (*Dermanyssus gallinae*) and non-target invertebrates. *Medical and Veterinary Entomology*, in press.
- GOTOH, T., SUGUSAWA, J., NODA, H. and KITASHIMA, Y. (2007) *Wolbachia*-induced cytoplasmic incompatibility in Japanese populations of *Tetranychus urticae* (Acari: Tetranychidae). *Experimental and Applied Acarology* 42:1-6.
- GURR, G.M., WRATTEN, S.D. and ALTIERI, M.A. (2004) *Ecological engineering for pest management*, pp. 232 (CABI Publishing).
- GUY, J.H., KHAJAVI, M., HLALELE, M.M. and SPARAGANO, O. (2004) Red mite (*Dermanyssus gallinae*) prevalence in laying units in Northern England. *British Poultry Science* 45: Supplement 1: S15 (Abstract).
- HARRINGTON, D., MOHI EL DIN, H., GUY, J., ROBINSON, K. and SPARAGANO, O. (2009a) Characterization of the immune response of domestic fowl following immunization with proteins extracted from *Dermanyssus gallinae*. *Veterinary Parasitology* 160: 285-294.
- HARRINGTON, D., CANALES, M., DE LA FUENTE, J., DE LUNA, C., ROBINSON, K., GUY, J. and SPARAGANO, O. (2009b) Immunisation with recombinant proteins subolesin and Bm86 for the control of *Dermanyssus gallinae* in poultry. *Vaccine* doi:10.1016/j.vaccine.2009.04.014.
- HASSANAIN, M.A., GARHY, M.F.E., ABDEL-GHAFFAR, F.A., EL-SHARABY, A. and MEGEED, K.N.A. (1997) Biological control studies of soft and hard ticks in Egypt. *Parasitology Research* 83: 209-213.
- HÖGLUND, J., NORDENFORS, H. and UGGLA, A. (1995) Prevalence of the poultry red mite, *Dermanyssus gallinae*, in different types of production systems for egg layers in Sweden. *Poultry Science* 74: 1793-1798.
- HOLT, K.M., OPIT, G.P., NECHOLS, J.R. and MARGOLIES, D.C. (2006) Testing for non-target effects of spinosad on twospotted spider mites and their predator *Phytoseiulus persimilis* under greenhouse conditions. *Experimental and Applied Acarology* 38: 141-149.
- HUNTER M.S., PERLMAN S.J. and KELLY, S.E. (2003) A bacterial symbiont in the Bacteroidetes includes cytoplasmic incompatibility in the parasitoid wasp *Encarsia pergandiella*. *Proceedings of the Royal Society of Biological Sciences* 270:2185-2190.
- ISMAN, M.B. (2000) Plant essential oils for pest and disease management. *Crop Protection* 19: 603-608.
- ISMAN, M.B. (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology* 51: 45-66.
- KILPINEN, O. and STEENBERG, T. (2009) Inert dusts and their effects on the poultry red mite (*Dermanyssus gallinae*). *Experimental and Applied Acarology* 48: 51-62.
- KIM, S., YI, J., TAK J. and AHN, Y. (2004) Acaricidal activity of plant essential oils against *Dermanyssus gallinae* (Acari: Dermanyssidae). *Veterinary Parasitology* 120: 297-304.

- KIM, S., NA, Y., YI, J., KIM, B. and AHN, Y. (2007) Contact and fumigant toxicity of oriental medicinal plant extracts against *Dermanyssus gallinae* (Acari: Dermanyssidae). *Veterinary Parasitology* 145: 377-382.
- KOCAN, K.M., MANZANO-ROMAN, R., and DE LA FUENTE, J. (2007) Transovarial silencing of the subolesin gene in three-host ixodid tick species after injection of replete females with subolesin dsRNA. *Parasitology Research* 100: 1411-1415.
- LEHANE, M. (2005) Managing the blood meal, in: Lehane, M. (Ed.) *The Biology of Blood-sucking in Insects*, pp. 84-115 (Cambridge University Press).
- LESNA, I., WOLFS, P., FARAJI, F., ROY, L., KOMDEUR, J. and SABELIS, M.W. (2009) Candidate predators for biological control of the poultry red mite *Dermanyssus gallinae*. *Experimental and Applied Acarology* 48: 63-80.
- LUNDH, J., WIKTELIUS, D. and CHIRICO, J. (2005) Azadirachtin-impregnated traps for the control of *Dermanyssus gallinae*. *Veterinary Parasitology* 130: 337-342.
- MAURER, V. and BAUMGÄRTNER, J. (1992) Temperature influence on life table statistics of the chicken mite *Dermanyssus gallinae* (Acari: Dermanyssidae). *Experimental and Applied Acarology* 15: 27-40.
- MAURER, V. and PERLER, E. (2006) Silicas for control of the poultry red mite *Dermanyssus gallinae*. *Proceedings of the European Joint Organic Congress, Odense, Denmark, May 30-31, 2006*. pp 504-505.
- MAURER, V., PERLER, E. and HECKENDORN, F. (2009) In vitro effects of oils, silicas and plant preparations against the poultry red mite *Dermanyssus gallinae*. *Experimental and Applied Acarology* 48: 31-41.
- MUL, M.F. and KOENRAADT, C.J.M. (2009) Preventing introduction and spread of *Dermanyssus gallinae* in poultry facilities using the HACCP method. *Experimental and Applied Acarology* 48: 167-181.
- NORDENFORS, H., HÖGLUND, J. and UGGLA, A. (1999) Effects of temperature and humidity on oviposition, molting, and longevity of *Dermanyssus gallinae* (Acari: Dermanyssidae). *Journal of Medical Entomology* 36: 68-72.
- PATHAK, D., MATHUR, V.C., LATHA, B.R. and JOHN, L. (2004) In vitro effect of indigenous plant extracts on ixodid ticks of small ruminants. *Indian Journal of Animal Sciences* 74: 616-617.
- SHRYOCK, T.R. (2004) The future of anti-infective products in animal health. *Nature Reviews Microbiology* 2: 425-430.
- SPARAGANO, O., PAVLIČEVIĆ, A., MURANO, T., CAMARDA, A., SAHIBI, H., KILPINEN, O., MUL, M., VAN EMOUS, R., LE BOUQUIN, S., HOEL, K. and CAFIERO, M.A. (2009) Prevalence and key figures for the poultry red mite *Dermanyssus gallinae* infections in poultry farm systems. *Experimental and Applied Acarology* 48: 3-10.
- STAFFORD, K.A., LEWIS, P.D. and COLES, G.C. (2006) Preliminary study of intermittent lighting regimes for red mite (*Dermanyssus gallinae*) control in poultry houses. *The Veterinary Record* 158: 762-763.
- STEENBERG, T. and KILPINEN, O. (2003) Fungus infection of the chicken mite *Dermanyssus gallinae*. *IOBC/wprs Bulletin* 26: 23-26.
- STEENBERG, T., KILPINEN, O. and MOORE, D. (2006) Fungi for control of the poultry red mite, *Dermanyssus gallinae*. *Proceedings of the international workshop 'Implementation of biocontrol in practice in temperate regions – present and near future'*, Flakkebjerg 1-3 November 2005. *DIAS report* 119: 71-74.
- TUCCI, E.C., PRADO, A.P. and ARAÚJO, R.P. (2008) Development of *Dermanyssus gallinae* (Acari: Dermanyssidae) at different temperatures. *Veterinary Parasitology* 155: 127-132.
- VALIENTE MORO, C., DE LUNA, C.J., TOD, A., GUY, J.H., SPARAGANO, O.A.E. and ZENNER, L. (2009a) The poultry red mite (*Dermanyssus gallinae*): a potential vector of pathogenic agents. *Experimental and Applied Acarology* 48: 93-104.

- VALIENTE, MORO, C., THIOULOUSE, J., CHAUVE, C., NORMAND, P. and ZENNER, L. (2009b) Bacterial taxa associated with the hematophagous mite *Dermanyssus gallinae* detected by 16S rRNA PCR amplification and TTGE fingerprinting. *Research in Microbiology* 160, 63-70.
- VILLANUEVA, R.T. and WALGENBACH, J.F. (2006) Acaricidal properties of spinosad against *Tetranychus urticae* and *Panonychus ulmi* (Acari: Tetranychidae). *Journal of Economic Entomology* 99: 843-849.
- VAN DER GEEST, L.P.S., ELLIOT, S.L., BREEUWER, J.A.J. and BEERLING, E.A. M. (2000) Diseases of mites. *Experimental and Applied Acarology* 24: 497-560.
- VAN EMOUS, R. (2005) Wage war against the red mite! *Poultry International* 44: 26-33.
- WILLADSEN, P. (2004) Anti-tick vaccines. *Parasitology* 129: S367-387.
- WILLIAMS, T., VALLE, J. and VIÑUELA, E. (2003) Is the naturally derived insecticide spinosad® compatible with insect natural enemies. *Biocontrol Science and Technology* 13: 459-475.
- WOJCIK, A.R., GREYGON-FRANCKIEWICZ, B., ZBIKOWSKA, E. and WASIELEWSKI, L. (2000) Invasion of *Dermanyssus gallinae* (De Geer, 1778) in poultry farms in the Torun Region. *Polish Parasitological Society* 46: 511-515.
- WRIGHT, H.W., BARTLEY, K., NISBET, A.J., MCDEVITT, R.M., SPARKS, N.H.C., BROCKLEHURST, S. and HUNTLEY, J.F. (2009) The testing of antibodies raised against poultry red mite antigens in an in vitro feeding assay; preliminary screen for vaccine candidates. *Experimental and Applied Acarology* 48: 81-91.
- ZOONS, J. (2004) The effect of light programmes on red mite (*Dermanyssus gallinae*) in battery cage housing. in: Perry, G.C. (Ed) *Welfare of the Laying Hen*, pp. 41 (CABI Publishing).