

CHAPTER 1

INTRODUCTION

Ladybirds, members of the family Coccinellidae are among the most familiar of the beetles and have common names around the world, such as lady cows, God's cow and the Virgin's insect (Moreton 1969). Ladybirds are one of the first insects that most children learn to recognise. They are unique among the insects in being almost universally regarded as benign. This is surprising because many people show an instinctive dislike of other members of the order Coleoptera (Majerus 1994). The wide popularity of the ladybird is manifest in the number of commercial and charitable organisations that use them as motif. For instance, in Britain, Woolworth uses the ladybird as a brand name for its range of children's clothes. Ladybird books have helped many youngsters in their early reading. In Germany, "Coccinelle" became a nickname for an early model of Volkswagen, which in Britain was nicknamed "the beetle" (Majerus 1994).

The family Coccinellidae comprises 5,200 described species worldwide (Hawkeswood 1987). These are medium size beetles with an oval, oblong or hemispherical body shape (Majerus 1994). Most of them are of brightly shining colours with a pattern of spots or patches against a contrasting background. Many appear to be distasteful to birds, and their conspicuous appearance is likely to be an example of warning coloration (Moreton 1969).

Numerous species of ladybirds are major biological control agents of pests such as aphids, mealybugs, scale insects, thrip, and mites in all parts of the globe (Alagen 1962; Moreton 1969). Some are specific in their choice of food, while many are polyphagous. The introduction of the vedalia ladybird, *Rodolia cardinalis* Mulsant, from Australia into

California in 1888 to control cottony cushion scale, *Icerya purchasi* Maskell, which threatened the citrus industry, is widely regarded as the first and still to this day, one of the most spectacularly successful instances of biological pest control (Majerus 1994).

A less familiar group of ladybirds is the very small black genus, *Stethorus* Weise, which are primary predators of spider mites (Acarina: Tetranychidae). They can also utilise other food such as flower nectar, pollen, honeydew and plant resins for survival (Moreton 1969; Helle & Sabelis 1985b). Most of the species are relatively small, 0.8-1.5 mm in length. They are remarkably well adapted to live and search for prey in the habitats of plant feeding mites and have been reported in many countries where spider mites have been studied (Jeppson *et al.* 1975). *Stethorus* spp. lay high numbers of eggs per female and have potentially high daily oviposition rates when food is abundant (McMurtry *et al.* 1970).

Most spider mite species (Tetranychidae) are polyphagous and occur on a wide variety of plants. Among the tetranychids, however, some are quite host specific. *Schizotetranychus* spp. for example mostly occur on monocotyledonous plants except for *S. baltazari* Rimando which is an injurious pest of citrus. The genus *Platytetranychus* Oudemans occurs on conifers. The genera *Oligonychus* Berlese, *Eotetranychus* Oudemans, and *Tetranychus* Dufour, however, occur on a range of hosts. Within a host these mites may have microhabitat preferences. For example, *Oligonychus mangiferus* (Rahman and Sapra) occurs only on the upper leaf surfaces of grapevines, while the lower surfaces of the same leaf may be infested by *Eotetranychus truncatus* Estebanes (Gupta 1985).

Two-spotted mite, *Tetranychus urticae* Koch is the most polyphagous species of the tetranychids (Readshaw 1975). More than 200 economic plants are recorded as hosts of *T. urticae* (Hill 1987). It feeds on a large number of greenhouse crops, a wide range of field

crops, vegetables, pot plants, strawberry, deciduous fruit trees, walnuts, almond, berries, hops, cucurbits, cutflowers, ornamental shrubs and vines (Pritchard & Baker 1952; Huffaker *et al.* 1969; Helle & Sabelis 1985a; Costello *et al.* 1992). *T. urticae* is a cosmopolitan species which occurs in Australia (Helle & Sabelis 1985a). It is a key pest in glasshouse crops (Gough 1992) but also attacks annual flowers, cutflowers, roses, azalea, dahlias, polyanthus, violets, strawberry, beans, cotton, deciduous fruit trees, citrus, vegetables, ornamental plants, and shrubs including many weeds in orchards (Bailey & Caon 1986; Spooner-Hart 1990; Hutchison 1992; Thwaite 1993; Bower & Thwaite 1995; McMaugh 1998).

In Australia *T. urticae* is costly to control in deciduous fruit orchards. It mainly feeds on leaves, causing bronzing and premature leaf fall that reduce the yield and quality of fruit. It may have to be disinfested from export fruit and can cause irritating skin rashes on orchard personnel. It is a serious pest in 40,000 ha. of apples and pear and 16,000 ha. of peaches, incurring an annual expenditure on acaricides of about \$A 3 million (Readshaw 1975).

The effective control of spider mites has become increasingly difficult due to withdrawal of some effective miticides and the development of resistance against a wide range of miticides and insecticides (Readshaw 1975). This suggests that the problem of controlling *T. urticae* deteriorates if the cost of developing and marketing of new compounds becomes prohibitive (Readshaw 1975). Therefore interest has increased in biological control of this pest. Many insects as well as several families of mites are recorded as predators of spider mites (Hussey & Huffaker 1976). One of these are ladybirds in the genus *Stethorus*, a cosmopolitan group found throughout all continents (Gordon & Anderson 1979; Houston 1980; Helle & Sabelis 1985b).

LITERATURE REVIEW

1.1 Morphology and Taxonomy of the Genus *Stethorus*

Ladybirds (Coleoptera: Coccinellidae) are such important predators that considerable attention has been given to many aspects of their biology and ecology. Ladybirds are small to medium sized often-brightly coloured beetles. They are oval or convex in shape with their head partly concealed by the pronotum, and they have three distinct tarsal segments, with the third tarsal segment deeply bilobed (Majerus 1994).

The tiny black coccinellids that belong to the genus *Stethorus* are important predators of spider mites (Acarina: Tetranychidae) (Moreton 1969; Britton & Lee 1972; Helle & Sabelis 1985b). Chapin revised the genus *Stethorus* in 1969, while historic descriptions of its taxonomy and morphology were published in 1979 (Gordon & Anderson 1979) and 1983 (Gordon et al. 1983). Dobzhansky (1924) placed it in the tribe Stethorini. Korchevsky (1931) synonymised Stethorini with Scymnini, but Kapur (1948), Sasaji (1968) and Gordon et al. (1983) consider Stethorini a valid tribe. *Stethorus* is easily separated from all other genera of Scymnini because the clypeus is not emarginate around the antennal base, and the prosternum is acutely produced in front, partly concealing the mouthparts (Gordon & Anderson 1979; Gordon et al. 1983).

Stethorus spp. are minute shiny black beetles, with spherical or oval bodies, covered with fine yellow hairs. They all look very similar, but can be differentiated by their morphological features, including body colour and size, dorsal structure, surface, leg and mouthpart colouration and abundance and appearance of setae (Moreton 1969; Gordon et al. 1983). The major morphological characters of species of *Stethorus* are given in Table 1.1.

Table 1.1 The major morphological characters of some adult *Stethorus* species.

<i>Stethorus</i> species	Body size		Colours of the body parts			Sources
	Length (mm)	Width (mm)	Antenna & mouthparts	Tibiae & Femora		
<i>S. keralicus</i> , Kapur	0.92-1.07	0.52-0.67	pale yellow	pale yellow		Daniel 1976
<i>S. vagans</i> (Blackburn)	1.12	-	pale yellowish	yellow-brown		Britton & Lee 1972
<i>S. nigripes</i> Kapur	1.15	-	black	black		Britton & Lee 1972
<i>S. histrio</i> Chazeau	1.00-1.20	0.80-0.86	yellowish brown	yellowish brown		Gordon & Anderson 1979
<i>S. fenestralis</i> Houston	0.90-1.10	0.65-0.80	yellow-reddish yellow	yellow-reddish yellow		Houston 1980
<i>S. obscuripennis</i> (Lea)	1.23-1.31	0.78-0.88	yellow	yellow		Houston 1983
<i>S. punctum punctum</i>	1.35-1.55	0.95-1.15	yellow	brown		Gordon et al. 1983
<i>S. punctillum</i> Weise	1.35-1.57	0.90-1.12	brownish yellow	brownish yellow		Gordon et al. 1983
<i>S. darwini</i> (Brethes)	1.65	1.10	yellow	yellow-brown		Gordon et al. 1983
<i>S. convexus</i> Yu	1.30-1.57	0.94-1.13	yellowish brown	yellowish brown		Guoyue 1996

Houston provided descriptions of the Australian species including *S. vagans* in 1980. "The femoral line of *S. vagans* reaches about three-quarters the distance between the hind coxa and the posterior margin of abdominal sternite one; the lateral part of the metasternum and area within the femoral line is without reticulation and the male abdominal sternite 6 has a deep triangular emarcation. In *S. nigripes* the metasternum is convex posteriorly with oblique grooves anteriorly on either side of the midline, the male abdominal sternite 6 is evenly rounded. In *S. histrio* the metasternum is flattened posteriorly, and without anterior grooves; while the male abdominal sternite 6 is truncate posteriorly. In *S. fenestralis*, the femoral line reaches about half the distance between the hind coxa and the posterior margin of the abdominal sternite; the lateral part of the metasternum and the area within the femoral line is partly reticulate and the male abdominal sternite 6 is evenly rounded".

Ladybirds lay their eggs in clusters, rows or singly on leaves and stems of plants and sometimes on stones or other non-living objects (Moreton 1969; Majerus 1994) *S. vagans* eggs are elongate, shiny white to pale yellow, and usually deposited horizontally on the substrate. *S. nigripes* eggs are pink and laid vertically (Britton & Lee 1972), in *S. punctillum* eggs are oval, pale yellow and laid flat on the underside of leaves (Moreton 1969), *S. keralicus* eggs are creamy, oval, and laid singly on the lower surface of the leaves (Daniel 1976) and eggs of *S. pauperculus* are smooth, elongated and bluntly round at both ends the newly deposited eggs pink and laid either singly or occasionally in groups of 2-5 on the lower surfaces of leaves (Puttaswamy & ChannaBasavanna 1977).

Larvae of *Stethorus* moult three times during their larval period before pupating in the last larval skin (Moreton 1969; Richardson 1977). The last instar larvae are elongate-oval, wide across the thorax and from 1.60 to 2.50 mm long (Moreton 1969; Gordon & Anderson 1979). The measurement recorded for different *Stethorus* spp. were for, *S. vagans*, 1.82-2.34 mm; *S.*

nigripes, 1.56-1.95 mm; *S. histrio*, 1.43-2.21 mm and *S. fenestralis* 1.69-2.34 mm (Houston 1980), while *S. punctillum* were, 2.5 mm (Moreton 1969), *S. keralicus* 1.53-2.04 mm (Daniel 1976) and *S. pauperculus*, 1.80 mm long (Puttaswamy & ChannaBasavanna 1977). Houston (1990) has given a brief description of the last instar of New Zealand species of *Stethorus*. Almost all *Stethorus* larvae have numerous setae with brown-black sclerotised areas at their base. Larva colouration ranges from white-pale white in *S. keralicus*, (Daniel 1976), pale cream white in *S. vagans* (Britton & Lee 1972), yellowish grey in *S. nigripes* (Britton & Lee 1972), blackish-grey in *S. punctum* (Colburn & Asquith 1971) and dark-brown in *S. pauperculus* (Puttaswamy & ChannaBasavanna 1977).

The pupae of *S. punctum*, *S. vagans*, *S. nigripes*, *S. keralicus* and *S. pauperculus* range from dark brown to black and possess fine setae on their dorsal side (Colburn & Asquith 1971; Britton & Lee 1972; Daniel 1976; Puttaswamy & ChannaBasavanna 1977).

1.2 Distribution of *Stethorus*

The genus *Stethorus* has a worldwide distribution, and is present throughout the tropical and temperate regions of the world (Gordon & Anderson 1979; Houston 1980; Guoyue 1996). It is found in areas with very different climates, e.g. from Canada to New Guinea; and in many ecosystems, including tropical rain forests, dry savannas, orchards and various crops (Helle & Sabelis 1985b).

Approximately 90 species are known around the world of which 24 have been recorded from China, including a new species *S. convexus* (Guoyue 1996). Kapur described 20 species from North America, while 5 members were recorded from Central and South America, including *S. tridens*, *S. ogloblini* and *S. darwini* (Gordon & Anderson 1979; Gordon 1982). Fatemi (1983) listed 19 species of coccinellids from Esfahan province, Iran of which *S. punctillum*,

was the only one preying on *Tetranychus turkestani*. Gordon & et al. (1983) reported 21 species of *Stethorus* from the Western Hemisphere, of which 11 were described as new species. A number of *Stethorus* species have been recorded from Australia, New Zealand, the Pacific and South East Asia. *S. bifidus*, *S. histrio* and *S. griseus* commonly occur in New Zealand (Houston 1990). *S. vagans*, *S. nigripes*, *S. histrio*, *S. fenestralis* and *S. obscuripennis* have been recorded from Australia. *S. vagans* and *S. nigripes* were previously described by Blackburn (1892) and Kapur (1948). However Britton & Lee (1972) redescribed these species and in doing so described a new species, *S. loxtoni* Britton and Lee. Houston (1980) revised the taxonomy and morphology of *S. vagans*, *S. nigripes* and *S. histrio* and concluded that *S. loxtoni* was synonymous with *S. nigripes*. He also described a new species, *S. fenestralis*, and redescribed *S. obscuripennis* from Norfolk Island in Australia (Houston 1980, 1983). *S. vagans* and *S. histrio* are widespread and common species in Australia, but are also found in New Caledonia. The latter species is also found on Reunion Island (Indian Ocean) (Houston 1980). *S. nigripes* is restricted to hotter inland areas, while *S. fenestralis* has been commonly recorded on coastal and sub-coastal areas of hot inland Australia (Readshaw 1975; Houston 1980).

1.3 Rate of Development of *Stethorus* spp.

Few studies have been undertaken to establish rates of development and degree-day models for coccinellids, especially for the genus *Stethorus*.

Developmental studies have been conducted on *S. bifidus* on a range of temperatures from 8.5 to 27.5°C with *Tetranychus lintearius* used as prey. The relationship between temperature and developmental rate was linear between 12.5 and 27.5°C for eggs, 4th instar larvae and pupae. Development threshold temperatures ranged from 9.4°C for third-instar larvae to 11.9°C for eggs, while development from egg to adult took 217 degree days (Petersons *et al.*

1994). Richardson (1977) also investigated minimum threshold temperature for development of *S. loxtoni* (= *S. nigripes*)*. This was 12°C for the pupal stage, followed by the egg and 1st instar larva at 11.5°C, and 6.0, 6.0, and 6.5°C for 2nd, 3rd, and 4th instar larvae respectively.

1.4 Biology of *Stethorus*

Biological studies have been conducted on several species of *Stethorus*. Most of the species complete their life cycle (egg-egg) in two weeks and have five generations a year under optimal temperature conditions, which is slightly longer than that required for the development of most mite species (Jeppson *et al.* 1975; Pavlova 1975; Singh & Ray 1977). The number of generations recorded per year for *S. punctum* was 3 (Colburn & Asquith 1971), 2 for *S. punctillum* (Moreton 1969), 14-16 for *S. siphonulus* (Puttaswamy & Rangaswamy 1976) and 15-18 for *S. pauperculus* (Puttaswamy & ChannaBasavanna 1977), per year. Two Chinese species, *S. guangxiensis* and *S. aptus* predators of the citrus mite *Panonychus citri* undergo 9-10 generations per year (Lie *et al.* 1990).

The sex ratio in all *Stethorus* species seems to be 1: 1 male: female, as has been demonstrated in *S. nigripes* (Richardson 1977) and *S. loi* (Shih *et al.* 1991). Mating can occur within 24 hours of adult emergence at high temperatures and multiple matings have been observed in many species (Helle & Sabelis 1985b). Females can lay up to several hundred eggs in clusters rows, or singly on leaves, stems, and other objects as reported previously (Section 1.1). The mean number of eggs recorded for various species of *Stethorus* in their life span are: *S. siphonulus*, 170 (Raros & Haramoto 1974), *S. keralicus*, 295 (Puttaswamy & Rangaswamy 1976), *S. nigripes* 281 (Richardson 1977) and *S. punctillum* 100 (Jiang *et al.* 1982). The developmental time of some *Stethorus* species is summarised in Table 1.2.

*Throughout this thesis the name of *S. nigripes* will be used for this thesis.

Table 1.2 Developmental time (days) of *Stethorus* spp. at different temperatures.

	Egg	Larva	Pupa	Adult	Total	Temperature	Source
<i>Stethorus punctum</i>	5.0	12.0	5.5	-	47	-	Colburn & Asquith 1971
<i>S. siphonulus</i>	2.8	6.8	3.0	29.8-32.4		27-30°C	Raros & Haramoto 1974
<i>S. keralicus</i>	3-4	5-6	3.5-4.0	38		26-34°C	Daniel 1976
<i>S. pauperculus</i>	4.36	7.63	3.8-4.0	29.8-32.4	43	24-26.2°C	Puttaswamy ChannaBasavanna 1977
<i>S. nigripes</i>	3.5	8.4	3.4	45.1	16.0	25°C	Richardson 1977
<i>S. punctillum</i>	3-4	8-9	6-8	32-53		24-28°C	Jingo <i>et al.</i> 1982
<i>S. gilvifrons</i>	2.9-3.5	5.3-12.1	2.0-5.6	44.8-145.9		20-35°C	Ahmed & Ahmed 1989
<i>S. loi</i>	1.79	5.53	3.3	48.4-56.6	17	24°C	Shih <i>et al.</i> 1991

Coccinellids commencing overwinter as adults. The hibernation site selected by ladybirds varies greatly. They may shelter among conifer foliage, in curled dead leaves, hollow plant stems, grass tussocks, under loose bark, in crevices in trees or walls or at the base of dense plant growth including grass. In the shelter of deciduous woodlands, they may overwinter on exposed trunks, branches, or low herbage (Moreton 1969; Majerus 1994). During hibernation, they may congregate in groups to pass the winter. Some may form aggregations of several thousand, while others are usually found in small groups of up to several dozen (Majerus 1994). It has been suggested that they are attracted to one another in the autumn by aggregation pheromones, possible due to dead individuals previously left at the site (Moreton 1969; Majerus 1994).

Some ladybirds hibernate in the temperate climates as adults, while other just become inactive at lower temperatures and resume activities on warm days. A number of *Stethorus* species do not overwinter, e.g, *S. nigripes*, *S. pauperculus*, *S. gilvifrons* *S. picipes* and *S. punctillum* (Richardson 1977; Puttaswamy & ChannaBasavanna 1977; Helle & Sabelis 1985b; Lyoussofi *et.al.* 1992). Their activity is continuous in tropical areas such as with *S. madecassus* and *S. punctum punctum* (Helle & Sabelis 1985b; Felland *et al.* 1995). Some species with large geographical ranges may or may not hibernate. *S. punctillum* has been recorded throughout the year in pear orchards in France, although in low numbers in winter, whereas in China it has been reported to hibernate as adults in winter under the bark of peach trees and in the soil around apple and pear trees, at distances 0-264 cm from trees and at a depth of 0-16.5 cm (Moreton 1969; Anonymous 1984). Adults of *S. punctum* commence hibernation in mid autumn in the leaf and grass debris beneath apple trees. Approximately 75% of overwintering beetles can be found in debris within a 60 cm radius of trees (Colburn

1971). Felland *et al.* (1995) collected more than 70% of hibernating *S. punctum punctum* adults from tree trunks, fallen leaves and root suckers of apple trees. However McMurtry *et al.* (1974) suggested that there appears to be no true diapause observed in any *Stethorus* species except for a facultative reproductive diapause induced by short day-length in *S. picipes*.

1.5. Primary and Alternative Hosts

The relationship between ladybirds and their hosts have attracted considerable attention, largely because of the economic importance of some of their prey. Ladybirds are regarded as beneficial because most eat plant pests such as aphids, scale insects and mites. They also feed on a variety of plant materials including honeydew, pollen, nectar, sap & resin and will even scavenge on dead organisms if their principal food is not available (Majerus 1994).

The feeding habits of *Stethorus* differ from other families of coccinellids. Most coccinellids are predaceous on insects in the sub-order Homoptera, but species in the genus *Stethorus* feed almost exclusively on spider mites (Tetranychidae: Acarina) (Gordon & Anderson 1979). Forty percent of known species of *Stethorus* have been reported to attack spider mites of economic importance and, to lesser extent, tenuipalpids (Tenuipalpidae: Acarina). Both adults and larvae are highly specialised predators of tetranychid mites (Houston 1980; Helle & Sabelis 1985b). When primary prey is scarce *Stethorus* are reported to eat a variety of other insects and mites such as aphids, scales, white flies and phytoseiid mites (Helle & Sabelis 1985b; Majerus 1994). They are also feed on honeydew, pollen, nectar, mildew, sweet sap, and plant resins or may even become cannibalistic (Helle & Sabelis 1985b; Majerus 1994).

Putman (1955a) observed feeding of starved adults and larvae of *S. punctillum* on aphids. He concluded that this diet was inadequate to complete development or induce oviposition,

although it increased adult longevity. He also observed predation on phytoseiid mites (Acarina: Phytoseiidae). Kamiya (1966) listed several aphids and diaspidids as prey for *Stethorus japonicus*, but did not state the importance of these prey, and also reported that feeding on plant resins and sweet foliar secretions extended adult longevity. Kehat (1967) reported predation of adult *S. punctillum* on the scale *Parlatoria blanchardi*.

While some species of *Stethorus* feed on a range of tetranychid species, others are more selective in their choice of host. For example *S. punctillum*, *S. punctum* and *S. gilvifrons* do not readily feed or oviposit if they are reared on some mite species, such as *Bryobia* spp. (Putman 1955a; McMurtry *et al.* 1970). *S. punctillum* and *S. fuerschi* seem to restrict their feeding to palm mite species only (Helle & Sabelis 1985b), and *S. keralicus* appears to be a specific predator of mites in the genus *Raoiella* (Nageshchandra & ChannaBasavanna 1983). Adults and larvae of *S. nigripes* failed to feed on eggs of *Panonychus ulmi* or *P. citri* and avoided all stages of *Bryobia rubrioculus* in the laboratory; honey and water alone were also not adequate for their survival (Hoy & Smith 1982). *S. gilvifrons* was identified as a specialist predator of *T. urticae* on beans in Turkey (Aydemir & Toros 1990).

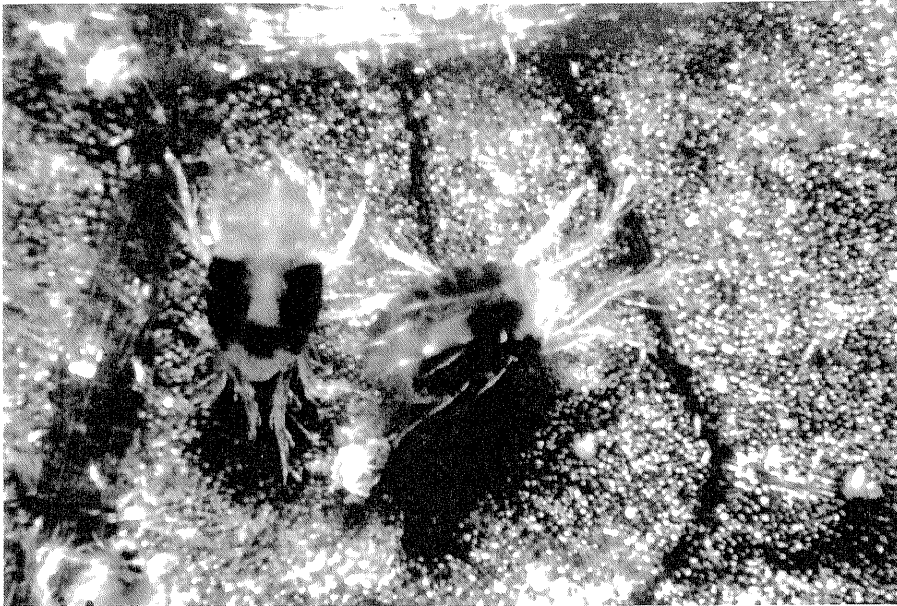


Fig 1.1 Two-spotted mite adult females *T. urticae* the primary host of *S. vagans*.

1.6. Functional and Numerical Response to Prey Density by *Stethorus* spp.

The importance of predacious organisms in the control of pests depends on many factors, including their functional and numerical response to prey, their reproductive rate, prey selection and searching capacity. Functional response is one of the most important aspects in the dynamics of predator-prey interactions (Holling 1959).

The extent to which a pest population suffers as a result of predation by natural enemies depends on the number of predators present and their ability to find and consume hosts. Solomon (1949) identified prey density as the crucial factor determining response by predators. In an attempt to distinguish between its effect on predator abundance and its effect on predation efficiency, he defined the terms “functional” and “numerical” response. The

functional response is the change in number of prey consumed per unit time by each predator in relation to changes in prey density. The numerical response describes the growth and death rates of the predator population as a function of prey density.

Several field investigations have confirmed that *Stethorus* spp. regulate *T. urticae* populations and appear to be active at low prey densities. Adults are capable of locating small isolated patches of prey even at very low levels (less than one mite per leaf) (Hull *et al.* 1977b; Helle & Sabelis 1985b; Congdon *et al.* 1993). The natural levels of mites in unsprayed apple orchards have been reported to be brought down to 1 mite per leaf or less where *Stethorus* spp were present (Readshaw 1973). *S. nigripes* was first recognised in Australian commercial fruit growing areas where it was the only predator of *T. urticae*. It maintained mite populations at 0.1 per leaf, well below the level at which economic loss is incurred (Richardson 1977).

Raworth (1990) conducted a major investigation of predator-prey-relationships in a strawberry field in British Columbia over a three-year period. He found that *S. punctum picipes* responded numerically to introductions of *T. urticae*. A similar study in red raspberries showed that *S. punctum picipes* was capable of detecting and attacking populations of *T. urticae* at very low density, distributed in small and widely scattered patches. In addition to conventional leaf sampling methods, the interaction of *S. punctum picipes* with its prey was examined by observing its response to prey patches introduced into the field from laboratory cultures. *S. punctum picipes* appeared to be active at low prey densities (Congdon 1993).

It has also been suggested that dispersal and searching ability, rather than numerical response, are key components of the prey-predator association. Zadeh *et al.* (1995) studied the functional response of adult *S. gilvifrons* in an apple orchard in Iran against *P. ulmi*. There

were correlated population fluctuations of both species beginning in early spring and continuing throughout summer. Populations of the pest decreased due to the wide distribution of the predator throughout the orchard. He concluded that *S. gilvifrons* was an effective natural control agent of *P. ulmi*.

In a laboratory study the effectiveness of *S. gilvifrons* was investigated against *T. turkestanii*. The predators were observed at prey densities of 5, 10, 20, 40, and 80 mites/ unit area at 30°C and 70 ± 5% RH. The development of *S. gilvifrons* was greatly affected by prey density. Predation and reproduction rates were highest at a prey density of 80 mites/unit area and lowest at a prey density of 5 mites/unit area. From the data it was concluded that *S. gilvifrons* was an efficient predator of *T. turkestanii* (Ahmed & Ahmed, 1988). Chen *et al.* (1993) observed that *S. chengi* exhibited a clear aggregate response to *P. citri* prey and spent more total time on high-density prey patches. There were negative correlations between the predator density, average individual searching efficiency, and average individual predation. Density-dependent, density-independent, and inversely density-dependent predation was mainly caused by mutual interference and aggregation among the predators. *S. gilvifrons* adults and larvae showed Type III and Type II responses respectively, when fed *Panonychus ulmi* in the laboratory (Zadeh *et al.* 1995).

In general, *Stethorus* species do not remain in a locality when mites are scarce (McMurtry *et al.* 1970). However, in specific cases they appear to be capable of maintaining mite populations below that at which economic crop losses occur (McMurtry & Johnson 1966; Colburn & Asquith 1971; Readshaw 1971 1973; Richardson 1972; Hull *et al.* 1976). In many cases, however, *Stethorus* species do not exert a suppressive effect on mite populations before the economic injury level is exceeded. This has been largely attributed to the fact that high

prey densities are generally required before the predators begin to increase substantially in numbers (Clancy & Pollard 1952; Putman 1955a).

1.7. Host Finding and Host feeding by *Stethorus*

The way that ladybirds find food is the subject of considerable controversy. A number of authors have reviewed feeding behaviour and rate of consumption in coccinellids. Hodek (1973) conducted a number of experiments and concluded that coccinellids find their prey by direct contact. Banks (1957) supported this idea and found that prey could be missed if they were only a few millimetres away, even if the coccinellids were down-wind of the prey. Allen *et al.* (1970) reported that hungry adults stopped momentarily and took quick snatches at a distance of 1.30-1.90 cm from the prey, and apparently did not require previous physical contact or visual stimuli.

Stubbs (1980) came to a different conclusion. He used adults and final instar larvae of seven-spot ladybird (*Coccinella septempunctata*) and found that the adults detected their prey by sight and larvae detected prey by smell. Nakamuta (1984) using video film of the seven-spot ladybird and concluded that it attacked the prey from a distance of 7 mm, but not at all in the dark. He emphasised that sight was important in prey detection. The views of both Stubbs and Nakamuta were also supported by Ciuffardi (cited in Majerus 1994) who reported that adults of two-spotted ladybird (*Coccinella bipunctata*) detect prey by smell at least from a short distance (Majerus 1994). It has been demonstrated that *Stethorus* may also detect their prey by chemicals such as kairomones (Sabelis & van de Baan 1983).

The genus *Stethorus* are also believed to find their prey by contact (Houston 1983). They search in random patterns for prey but after finding and consuming a few mites, searching intensity increases in the vicinity similar to that occurs in a number of other coccinellids. *Stethorus* spp. exhibit positive phototropism similar to their mite prey, so they tend to deposit their eggs among mite populations even in situations not favourable for their larvae. For example, oviposition on plants with hooked trichomes will impede larval movement and feeding activity, and may even kill larvae (Moreton 1969).

Alternative hosts and numerical response to prey in *Stethorus* have previously been discussed in sections 1.5 and 1.6. Other aspects of feeding behaviour and rate of consumption by several *Stethorus* species have been studied by a number of authors indicating Fleschner (1950), Robinson (1953), Collyer (1953), Putman (1955a), Kaylani (1967) and Hodek (1973). Both adults and larvae appear to feed on all stages of spider mites, but prefer immature stages. The first instar larvae feed predominantly on eggs, while later instars and adults feed on all stages of *T. urticae* (Dhooria 1981; Richardson 1977). Adult *Stethorus* actively fly and aggregate on mite colonies and eat mite eggs, while larvae consume motile stages (Helle & Sabelis 1985b). A preference for large mobile prey has been observed in *S. madecassus* (Chazeau 1974) and *S. nigripes* (Richardson 1977). They suck, chew, damage or eat whole adult mites. In temperate conditions, *S. punctillum* mostly devoured overwintering mite eggs in autumn (Collyer 1953). The daily rate of prey consumption by ovipositing females may exceed 40 adult mites or a greater number of immature stages per day. Consumption by fourth instar larvae may be even higher during later larval development (in excess of 200 mites) than the total consumption for the rest of the larval development (McMurtry *et al.* 1970). Zhou *et al.* (1991) recorded that last larval instars of *S. punctillum* consumed a mean of 84.6 mites /day.

Laboratory and field studies have been conducted with different species of *Stethorus* against different species of tetranychid mites to assess their rate of consumption. For example in a greenhouse environment, adult *S. punctum* consumed an average of 20 adult female mites per day (Bravenboer 1959). Moreton (1969), recorded that adult *S. punctum* required 20-40 mites per day but could consume as many as 140 mites per day at high temperatures. Larvae of the same species accounted for up to 250 mites a day, if they did not chew, but sucked the body haemolymph of their prey. He suggested that if starting with one female *S. punctum* and 100 female red spider mites, the latter would be eliminated after three generations. Colburn & Asquith (1970) studied the average feeding rate of *S. punctum* on *P. ulmi* and found that adult beetles consumed an average of 8.75 motile stages of mites and larvae consumed 9.67 per hour. *S. nigripes* is capable of consuming all stages of *T. urticae* but mite eggs are preferred over other stages (Richardson, 1977).

The potential of *S. punctum* as a biological control agent against the apple pest, *P. ulmi*, was evaluated in the laboratory. It killed significantly more *P. ulmi* at a mite density of 45/ arena than any other predator tested (Parrella *et al.* 1980). A laboratory study carried out in India used the leaf-disc technique to determine the duration of feeding by various predators on different stages of the citrus pest *Eutetranychus orientalis* (Klein) (Dhooria 1981). He found that 1st instar larva of *S. pauperculus* fed only on eggs and larvae of the mite, but later instars fed on deutonymphs and adult females. A 4th instar larva of this species required an average of 56, 44, 58.12, 95.71, 233.75, and 117.5 eggs, larvae, protonymphs, adult male and female mites respectively. Eleven predators of *Tetranychus* mites were noted in India with the most effective being *Stethorus* sp., the adults of which destroyed 40 mites and the final instar larvae 104 mites per day respectively (Rustamova 1981).

In a number of *Stethorus* spp., starved individuals have been reported to consume more mites than satiated ones (Helle & Sabelis 1985b). For example, satiated larvae of *S. punctum* spent most of their time searching (74.4 %) but when starved, time was equally shared between feeding and searching (Houck 1980). Feeding time increased significantly with the number of motile stages eaten, but not for mite eggs consumed. Starved adults concentrated their searching efforts within leaf searching patterns, while satiated adults travelled greater distances. *S. punctum* larvae, however, concentrated their efforts on prey once it was located and travelled further when starved (Houck 1980). Gikorashvili (1983) compared feeding by adult phytoseiids with *Stethorus* species in the USSR and concluded that adult phytoseiids destroyed an average of 3.6 *Panonychus ulmi* in a 24 hours, while larvae and adults of *Stethorus* destroyed 95 and 41 mites respectively. Gravid females consumed twice as many prey as did males (Helle & Sabelis 1985b).

Houck (1991) in laboratory studies examined the proportion of time *S. punctum* spent on searching, feeding and resting with *T. urticae* as host. Satiated female beetles spent 45.1% of their time searching, 14.4% feeding and 40.5% resting, while starved females spent a greater proportion of their time on feeding. Satiated larvae spent 78.4% of their time searching and 21.6% resting. The percentage of time spent by starved larvae on feeding and handling increased with increasing prey density.

1.8 Integrated Mite Control

Integrated pest management (IPM) can be defined as a strategy for managing pest populations by taking advantage of all available control measures. It emerged as a result of significant changes in attitude prompted by the excessive use of chemical pesticides during 1940-1960 period. The trend away from total reliance on chemicals for insect and mite control is

continuing throughout the world. Considerable research is now focused on non-chemical methods (including natural enemies) to control pests (DeBach & Rosen 1991).

The control of two-spotted mites using IPM strategies is probably a very good example of the use of biological agents. Spider mites (especially two-spotted mite, *T. urticae*) are key pests of a wide range of crops and ornamental plants throughout the world. They are notorious pests for their capacity to develop resistance against most of the registered insecticides and miticides (Penrose *et al.* 1999). Therefore chemical control has to be integrated with use of natural enemies, pathogens or plant resistant varieties (Penrose *et al.* 1999).

Markov & Isakulova (1982) reported that *T. urticae* was a serious pest on sugar beet which was mainly controlled by predators, and of them, *S. punctillum* was the most important. Yigit & Uygun (1982) studied the population dynamics of *Tetranychus viennensis* Zacher and its predators *Stethorus* spp., in 5 apple orchards of Adana province, Turkey. It was shown that the predators were able to control *T. viennensis* when broad-spectrum insecticides were not applied repeatedly. Populations of *T. urticae* built up after applications of pesticides on lucerne seed crops in South Australia to control *Therioaphis trifolii*, because of the susceptibility of the predator *S. nigripes* to these chemicals. When pesticide applications ceased *S. nigripes* was able to successfully control *T. urticae* in these crops (Bailey *et al.* 1982).

Atanasov (1983) reported that the spider mites *T. urticae* and *T. turkestanii* infesting strawberries in greenhouses could be controlled by releasing *Phytoseiulus persimilis* at a rate of 5 individuals /m²; these releases could be supplemented by the application of dicofol, dinobuton or diphenyldiazene 1-oxide, if necessary. Spooner-Hart (1991) reported that *P.*

persimilis has been successfully used in Australia against *T. urticae* in commercial horticultural crops, such as strawberries, vegetables, berries, hops, nursery and a variety of foliage plants and deciduous fruits.

Studies carried out on four species of spider mites, viz. *T. urticae*, *T. turkestanii*, *T. atlanticus* and *T. cinnabarinus* in maize crops showed *S. punctillum* to be the most abundant natural enemy. The appearance of this predator was fairly well synchronised with changes in the abundance of spider mites and the ratio between adults and larvae of the predator and motile mites was 1:15 (Nikolov *et al.* 1983). Both *Stethorus* spp. and *Amblyseius* spp. play a very important role in suppressing populations of mites *Eriophyes zeasinis* and *T. cinnabarinus* in Indian crops. Of several insecticides endosulfan, chinomethionat and carbaryl (Sevin) afforded the best control of mites with the least adverse effects on these predators (Rather 1983).

Sacco & Girolami (1988) evaluated four different control programs (including IPM) against apple mite, *P. ulmi* in an apple orchard. *P. ulmi* populations reached very high levels towards the end of the season, but declined due to the presence of *Stethorus* spp. The only phytoseiid mite observed was *Typhlodromus pyri*. Lorenzato (1988) reported a similar observation in apple orchards in which *P. ulmi* was the most common pest with its abundance inversely proportional to populations of its predators *S. darwini*, phytoseiid mites and chrysopids. Orman & Bakanligi (1989) studied prey consumption capacity, functional and numerical responses to prey density and the effect of starvation of *S. punctillum* on its apple pest host *Tetranychus viennensis*. The population dynamics of both species were also observed in apple orchards, and it was concluded *S. punctillum* was an effective predator of *T. viennensis*. Deng *et al.* (1990) reported that in integrated control of *P. citri* in China, *Stethorus* spp. were one of

the predators that could be integrated with cultural, chemical or other methods for the control of *P. citri*. Field (1979) commented on the role *Stethorus* spp in Victorian (Australia) peach orchards.

Injac & Dulie (1992) reported that *S. punctillum* together with *Orius minutus* and *Chrysopa carnea* reduced populations of *P. ulmi*, *T. urticae* and the rust mite *Aculus schlechtendali* in Serbian orchards if acaricides were not applied. Similar results were reported from red raspberry crops in Quebec Canada (Roy *et al.* 1999), where the spider mites *Tetranychus mcdanieli* and *T. urticae* were most abundant in pesticide treated commercial crops, followed by untreated crops and wild berries. *S. punctillum* was abundant in the unsprayed crops but rare in the pesticide treated and wild systems. *Amblyseius fallacis* (Garman) was the most abundant predator in the sprayed crops, whereas a complex of other predatory mite species dominated the wild system. A complex of naturally occurring beneficials, including *S. punctillum* controlled *T. urticae* in strawberry fields in Spain (Garcia & Zamora 1999). However, the predators colonized the crop when only when the mites reached medium to high levels. In Israel a netted peach orchard in which populations of *T. urticae* and *T. cinnabarinus* increased were suppressed by *Typhlodromus athiasae* and *S. gilvifrons* (Erez *et al.* 1993). Espinha & Torres (1995) observed that the population density of *S. punctillum* was closely associated with that of *P. ulmi* and concluded that *S. punctillum* controlled this species of mite effectively.

The nature of the host plant species can also influence effectiveness of control of *T. urticae* by *Stethorus* and other predatory species. Rott and Ponsonby (2000a; 2000b) reported that performance of both *S. punctillum* and the phytoseiid mite *Amblyseius californicus*, was superior on pepper and tomato and least on aubergine. This is likely to be a function of the leaf surface characteristics, especially pubescence, which may impede predator movement.

1.9 Rationale and Aims of the Thesis

The selection, rearing and manipulation of natural enemies as biological control agents against crop pests have been successful in agricultural and horticultural production systems worldwide. A number of agents have been used to reduce dependency on pesticides, which have become a major problem due to environmental contamination, pest resistance, and animal and human safety. The increasing number of natural enemies are being evaluated for their potential as a biological agents against their pests. The vedalia ladybird *Rodolia cardinalis* was highly successful against cottony cushion scale, *Icerya purchasi* (Majerus 1994).

Two-spotted mite, *T. urticae*, is distributed worldwide and is a major pest of a wide range of crops such as fruits, vegetables and ornamental plants (Helle & Sabelis 1985a; Hills 1987). In Australia it also attacks a number of field crops, nursery crops, flowers, fruits, vegetables and ornamental plants. The Queensland flower industry lost more than \$A 30 million per annum due to the damage of *T. urticae* (Parker 1991). A number of miticides have been introduced for control of *T. urticae*, but they have developed resistance against these miticides and some populations are now impossible to control with registered miticides (Parker 1991; Penrose *et al* 1999). However the predatory mites *P. persimilis* and *T. occidentalis* have been successfully used to control *T. urticae* in various crops. After the success of these introduced predatory mites, interest developed in other overseas predators, especially predatory mites. However, little attention has been paid to local predators such as *Stethorus* spp., which may be better adapted to our climate than those imported from overseas. In Europe it has been the practice that many biological control agents are selected by discovery in local environments. The recognition of such species may also be advantageous to building the world pool of natural enemies.

Ladybirds of the genus *Stethorus* are effective predators of two-spotted mite. Several species of *Stethorus* are known in Australia in the Pacific and South East Asia. However, except for *S.nigripes* (Richardson 1977), no detailed investigations have been conducted on any aspect of their biology, ecology, rearing, or their potential as biocontrol agents in Australia. The importance of *Stethorus* spp. in biological control has been more extensively investigated overseas (although much than less for many other species of predators) with a view to the introduction of more ecological sound, effective, and sustainable methods for spider mite management (Moreton 1969; Colburn & Asquith 1971; Gutierrez & Chazeau 1972; Raros & Haramoto 1974; Daniel 1976; Puttaswamy & ChannaBasavanna 1977; Puttaswamy & Rangaswamy 1977; Richardson 1977; Jiang *et al.* 1982; Ahmed & Ahmed 1989; Lie *et al.* 1990; and Shih *et al.* 1991).

This thesis reports investigation on biological aspects of *S. vagans*, one of the most common Australian species of *Stethorus*. Prior to this study there had been no published report on any aspect of *S. vagans* except its description, taxonomy and occasional references to its presence in crops infested with *T. urticae* (Readshaw 1975), although Lamacraft (1972) undertook a brief study on prey preference of two mite species, *T. urticae* and *Bryobia arbores* by *Stethorus* spp. The following parameters were investigated, based on laboratory and field studies:

- (i) Influence of temperature, humidity and day-length on the developmental longevity and mortality of *S. vagans* (Chapter 3).
- (ii) General biology, reproductive behaviour and diapause (Chapter 4).

- (iii) Host location and feeding behaviour (Chapter 5).
- (iv) Host preference for primary host stages and alternative host (Chapter 5).
- (v) Time partitioning, functional and numerical responses to prey density (Chapter 5)
- (vi) Effect of different natural and artificial hosts as well as starvation on mating, fecundity and longevity (Chapter 5).
- (vi) Searching behaviour and location of prey populations (Chapter 6).