1. Introduction

1.1 Pests of Tea

Tea, *Camellia sinensis* (L) O, Kunze (Theaceae), a woody perennial plantation crop cultivated as monoculture on small and large holdings is a gift of nature (Plate 1.1). It is the oldest non alcoholic caffaeine containing beverage popular all over the world for its special aroma, flavor and health benefits.

Tea is an important cash crop cultivated in more than 50 countries around the world spreading over from Georgia (43°N) to Nelson (New Zealand, South Island; 42°S) (Roy *et al.*, 2014). Asia cultivates tea in large scale followed by Africa and to a small scale by Europe, South Africa, Australia and New Zealand. India ranks first in production of black tea and second in area of plantation as compared to China. In India, tea is mainly produced in Assam, West Bengal, Tamil Nadu, Kerela and Karnataka (Plate 1.2). Other states such as Bihar, Himachal Pradesh, Orissa, Tripura, Arunachal Pradesh and Uttaranchal also grow tea in small areas. More than fifty percent of India’s total tea production is contributed from North East India.

In recent times, the demand for tea is increasing day by day. Therefore, it is necessary to boost up the production of good quality tea in order to meet the rising demand. Among the various constrains, the insect pests in tea are considered as one of the important biological factor that affect production of made tea (Das, 1965; Roy *et al.*, 2009; Roy *et al.*, 2015). A wide range of pests have been associated with tea plantations (Plate 1.1b). Tea is a monoculture, long lived perennial crop which provide a favourable environment, uninterrupted food supply and suitable sites for the reproduction and survival of different insect pests (Basu Majumder *et al.*, 2012).
Plate 1.1- (A) Photograph showing tea plantation area in Tocklai garden, Jorhat,

(B) Insect pests found in different parts of the tea plant
Major tea growing areas in the world

Major tea growing areas in India (green)

Major tea growing areas in Assam

Plate: 1.2 Map related to tea growing areas in World, India and Assam
Globally, more than one thousand species of arthropods are associated with tea plants (Chen and Chen, 1989; Hazarika et al., 2009). Among them, about 300 species of insect and mites are reported from India (Muraleedharan, 2010). Every part of a tea plant i.e leaf, stem, root, flower, and seed are subjected to attack by pests, which may result in severe crop loss, if left unchecked (Hazarika et al., 2009). The incidence and abundance of pests on tea are influenced by weather conditions. Most of the pests are highly seasonal and attack tea either during dry season or in wet weather, while some are perennial in nature. The tea pests are classified based on their feeding behaviour as chewing pest and sucking pests. The major chewing pests of tea are red slug caterpillar, flush worm, bunch caterpillar and the loopers. The sucking pests of tea comprised of tea mosquito bug, jassids, thrips and aphids (Gurusubramanian and Borthakur, 2005) which cause an average of 5% to 55% yield loss (Hazarika et al., 2009) in the crop.

1.2 Tea red spider mite (Oligonychus coffeae)

Mites are one of the major groups of tea pests present in almost all tea producing countries (Cranham 1966b; Muraleedharan et al., 2005). More than 12 species of mites are reported from Bangladesh, China, India, Indonesia, Japan, Malaysia, Sri Lanka, Taiwan, and erstwhile USSR that attack tea plant (Muraleedharan,1992; Handique et al.,2015). Among the mite species attacking tea plantations of North East India, the red spider mite (RSM), Oligonychus coffeae Nietner (Acari: Tetranychidae), deserves special attention since it occurs in all tea growing areas and causes considerable crop loss (Muraleedharan et al., 2005, Roy et
al., 2014a; Roy et al., 2016). It is the largest of all the mites discovered by Nietner 1861 on coffee plants in Sri Lanka which can be easily seen even by the naked eye. This mite normally affects the upper surface of mature tea leaves. Its infestation starts along the midrib and veins of leaves and gradually spreads to the entire upper surface. They migrate to the lower surface of older leaves and rarely to young leaves as well during severe infestation. As a result of feeding on chlorophyll, the maintenance foliage turns ruddy bronze rendering RSM infested fields distinct even from a distance (Plate 1.3). Severe infestation ultimately leads to defoliation (Selvasundaram and
Muraleedharan, 2003) bringing about the death of plants and crop loss. White
coloured cast skins are seen on the upper surface of severely damaged leaves. Mites
spin a web of silken threads on the leaf and protect themselves from adverse weather
conditions. It is estimated that the annual crop loss due to RSM varies from 14 to
18% (Muraleedharan et al., 2005). In addition to the direct loss, the damage caused
to tea leaves by mites could adversely affect the quality of made tea. Life history and
control measures of RSM have been reported earlier by several authors in different
tea-growing regions including Northern India (Das, 1959a, b; Das and Das, 1967;
Gotoh and Nagata, 2001; Selvasundaram and Muraleedharan, 2003; Muraleedharan
et al., 2005).

The life cycle of RSM composed of an egg, larva, protonymph, deutonymph
and adult. Eggs are bright reddish colour, spherical in shape and provided with a
short hair like filament. Before hatching, the eggs change their colour from glossy
red to light orange. Incubation period is 4-6 days but varies depending on
temperature (Gotoh and Nagata, 2001). Newly hatched larva is yellowish orange in
colour; round in shape with three pairs of legs. The larval period is followed by
protonymph stage. The protonymph stage is oval in shape and bear four pairs of
legs. Anterior part of the body is pale crimson while the posterior part is deep
reddish brown. Deutonymph, the second quiescent stage is similar to protonymph
but larger in size. Sexes can be differentiated at deutonymph stage. Adult female
RSM is elliptical or oval in shape with dark purplish brown abdomen. The male
differs from the female in size and also in shape of the body. The male has a
slimmer body and tapering abdomen. Both males and females are sexually mature
on emergence and mating takes place immediately after the emergence of females.
Males are short-lived whereas females are known to live for 25-30 days. There are several generations of RSM in a year. Duration of the life cycle shows variation with temperature. During summer it completes its lifecycle within 9-12 days while in winter it may be prolonged up to 25 days. In severe infestation, RSM alone can causes 17-46% crop loss annually (Sudoi, 1997; Muraleedharan et al., 2005; Sudoi et al., 2011; Roy et al., 2014a). In South India the economic threshold level (ETL) of RSM in tea is reported to be 4 mites per leaf (Muraleedharan and Selvasundaram, 2002; Muraleedharan, 2006) and in North East India it is accounted 2–3 mites/cm² (Banerjee, 1971). Infestation of mite in tea fields causes a loss of 340–511 kg of tea per hectare during drought period (Rao 1974a, b).
Plate-1.4 Photograph showing (A) adult red spider mite (*Oligonychus coffeae*),

(B) Different life stages of red spider mite
1.3 Management of Red spider mite

Mite management in tea gardens is mainly achieved by the application of synthetic pesticides. Among synthetic pesticides, different class of acaricides such as ethion, dicofol, deltamethrin, propargite, sulphur, hexythiazox, fenazaquin are being used to combat the menace of RSM. Though chemical pesticides are regularly applied; RSM has become a perennial pest in tea accounting for huge crop loss in the recent times. The mite also reported to develop resistance to pesticides very quickly because of short life cycle and producing numerous generations in a year and expose to a high frequency of pesticide spray applications (Cranham and Helle, 1985). On the other hand, tea is an important export commodity and it has to fulfil the international regulations on pesticide residues. Indiscriminate and extensive use of pesticides in tea have some drawbacks such as, development of resistance to pesticides, outbreak of secondary pests, destruction of natural enemies and other non-target organisms, harmful effects on human health and environment, presence of undesirable residues in made tea etc.

In the recent years, it has become a major concern to the tea industry as the importing countries are imposing strict restrictions for acceptability of the made tea due to pesticide residues. The tea importing countries are now a day very much concerned about pesticide residues in tea. Maximum Residue Limit (MRL) has been fixed for pesticides by regulatory authorities to provide acceptable standards of safety for pesticides.

All these issues necessitate the development of alternate strategies of pest management instead of sole dependence on chemical pesticides. Early detection of
the pest and immediate adoption and implementation of IPM practices is necessary for successful management of RSM.

1.3.1 Chemical control  The chemical control is one of the most widely adopted techniques to overcome the crop loss by RSM. A wide range of acaricides belonging to different group is currently being used to control this pest.

**Table (1.1) List of approved Plant Protection Formulations (PPFs) for use in tea plantations (Approved from Anonymous, 2014)**

<table>
<thead>
<tr>
<th>Types and names of PPFs</th>
<th>Acaricides</th>
<th>Insecticides</th>
<th>Fungicides</th>
<th>Herbicides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicofol 18.5 EC</td>
<td>Azadirachtin 5 EC</td>
<td>Copper hydroxide</td>
<td>Glyphosate 41% SL</td>
<td></td>
</tr>
<tr>
<td>Ethion 50 EC</td>
<td>Clothianidin 50 WDG</td>
<td>Copper oxycloride 50 WP</td>
<td>Glyphosate 71 % SG</td>
<td></td>
</tr>
<tr>
<td>Fenazaquin 10EC</td>
<td>Deltamethrin 2.8 EC</td>
<td>Hexaconazole 5 EC</td>
<td>Glufosinate Amonium 13.5 SL</td>
<td></td>
</tr>
<tr>
<td>Fenpyroximate 5EC/SC</td>
<td>Fenpropathrin 30 EC</td>
<td>Propiconazole 25 EC</td>
<td>Oxyfluorfen 23.5 EC</td>
<td></td>
</tr>
<tr>
<td>Hexythiazox 5.45 EC</td>
<td>Phosalone 35 EC</td>
<td>Bitteranol 25 WP</td>
<td>Paraquat Dichloride 24% WSC</td>
<td></td>
</tr>
<tr>
<td>Propargite 57 EC</td>
<td>Profenofos 50EC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur 80WG</td>
<td>Quinalphos 25 EC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wettable Sulphur 40 WP</td>
<td>Quinalphos 20 AF</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Micronised liquid sulphur 52%

Lime sulphur - Polysulphide - S

Spiromesifen 22.9

Bifenthrin 8 SC

|--------------------------------------------------|

However growing concern on food safety, increasing consumer awareness and fixation of very low Maximum Residue Limits (MRLs) have reduced the choice of pesticides in tea. Regulations declared by FSSAI, European Union, Codex etc on MRLs in tea; impose limitations on the use of pesticides in tea. Keeping this point in view, Central Insecticides Board (CIB) presently permitted 33 pesticides for use in tea plantation in India (Anonymous, 2014). Different sulphur formulations viz., Wettable Granule (WG), Wettable Powder (WP), Water Dispersible Granule (WDG), Dust Formulation (DF) and lime-sulphur solution were extensively used against RSM. Dicofol and ethion have also been applied on tea fields for management of RSM. Recently, a number of new acaricides such as propargite, fenpyroximate, hexythiazox, bifenthrin, fenazaquin, and spiromesifen are used for control of RSM in tea (Roy et al., 2014a, Babu and Muraleedharan, 2010; Anonymous, 2012).
1.3.2 Problem related to use of pesticides

Tea is an important export commodity that plays an important role in boost up the national economy of the country. In addition, the tea industry also provides employment to a large number of people. Therefore it is necessary to maintain both the productivity and quality of made tea. The tea pests are one of the factor that decelerate the production of tea and their control is solely depends on the use of synthetic chemicals. However production of tea has to be in compliance with the international regulation on pesticide residue. Pesticides application programme on tea in India is largely regulated by the recommendation of the two premier Research Institutes working on tea (Muraleedharan and Selvasundaran, 1996; Babu and Muraleedharan, 2010). Frequent use of pesticides for a long period of time could lead to undesirable effects such as contamination of environment, possibility of development of secondary pest outbreak, presence of undesirable residues in processed tea etc (Das, 1959; Gurusubramanian et al., 2008; Sarnaik et al., 2006). Although in intensive pesticide application program, the natural enemies were exposed to excessive amounts of pesticides and thereby lower the level of natural control of the pest in field (Das et al. 2005). These issues necessitate the development of alternate pest management strategies.

1.3.3 Biological control

Biological control is one of the important components of Integrated Pest Management (IPM) programme adopted to reduce the pest population in a natural way. It is one of the oldest pest management strategies which are employed with the aim of long term pest control by bringing the pest population below economic injury
level. The term “Biological control” was first used by Smith (1919) to signify the use of natural enemies to control insect pests (Clarke, 1993). Natural enemies like predator, parasites, parasitoids or pathogens that attack pests and maintain their population at a lower average level than would occur in their absence (De Bach, 1965). Tea pests are also suppressed by a number of natural enemies. A list of commonly found natural enemies of tea pests are given in table (1.2).

It is the only control tactic that increases, rather than decreases, the species diversity within an agro ecosystem. Based on the positive features of biological control, such as its target specificity, low impact on environment and the lack of negative effect on humans, it is the prime candidate in the search for reducing dependency on chemical pesticides. The ability of natural enemies to reproduce rapidly, to search out their hosts and survive at relatively low host densities makes outstanding advantages possible (Stelzel and Devetak, 1999; Saini and Salto, 1999 and Singh and Manoj, 2000). Change from chemical to biological control substantially contributes to the conservation of natural resources, and results in a considerable reduction of environmental pollution. It eliminates human exposure to toxic pesticides and improves sustainability of production systems. There are several example of biological control of insect pest in worldwide. The most spectacular successful case of biological control was the introduction of vedalia ladybird, *Rodalia cardinalis* to control cottony cushion scale, *Icerya purchace* which intimidate the citrus industry in California in 1988 (Majerus, 1994). The control of Woolly apple aphids *Eriosoma lanigerum*, in apple orchards of the northeastern and northwestern U. S. by a chalcid parasite *Aphelinus mali*, is another example of biological control of insect in Europe (Ritcher, 2006).
Table: 1.2 List of major pest and their natural enemies in tea

<table>
<thead>
<tr>
<th>Name of the pest</th>
<th>Natural enemies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red spider mite</td>
<td><em>Stethorus gilvifrons, Agistemus hystrix</em></td>
</tr>
<tr>
<td></td>
<td><em>Chrysoperla carnea (P)</em></td>
</tr>
<tr>
<td>Scarlet, pink and purple</td>
<td><em>Agistemus hystrix (P)</em></td>
</tr>
<tr>
<td>mite</td>
<td></td>
</tr>
<tr>
<td>Bunch caterpillar</td>
<td><em>Cantheconidia furcillata, (P), Dipterus fly (Ps)</em></td>
</tr>
<tr>
<td>Looper caterpillar</td>
<td>*Apanteles sp. (Ps), Bacillus thuringiensis (Pth)</td>
</tr>
<tr>
<td>Red slug caterpillar</td>
<td><em>Cantheconidia furcillata (P), Apanteles sp. (Ps)</em></td>
</tr>
<tr>
<td>Flush worm</td>
<td><em>Apanteles sp. (Ps)</em></td>
</tr>
<tr>
<td>Aphid</td>
<td>*Leis dimidiata, Menocillus sexmaculatus, Verania</td>
</tr>
<tr>
<td></td>
<td><em>vincta, Syrphid</em></td>
</tr>
<tr>
<td>Tea mosquito bug</td>
<td><em>Chrysoperla carnea, Oxyopes sp. (P)</em></td>
</tr>
</tbody>
</table>

(P: Predator, Ps: Parasitoid, Pth: Pathogen)

1.3.4 Role of parasitoids in biological control

Thousands of insects pests present in tea surroundings paved the way for development of several species of insect parasitoids (Muraleedharan et al., 1988 and 2001). Among the natural enemies present in tea a total of 133 parasitoids have been recorded from the tea ecosystem which includes braconids, bethylids, eulophids, ichneumonids, tachinids, and muscids (Hazarika et al., 2009a, Roy et al., 2014). The parasitoids comprised 39 percent of the total natural enemies complex of tea. The braconids, ichneumonids and tachinids are the most common parasitoids in the tea
plantations in North East India (Roy et al., 2005, 2014). *Homona coffearia* in Srilanka is effectively inhibited by a larval parasitoid *Macrocenurus homonae* (Hymenoptera) (Eden, 1976). The management of *Empoasca flavescens* population can be done by using drynid wasp parasitoid (Roy et al., 2014, Das, 1974; Hazarika et al., 1994). The order hymenoptera contains highest species of parasitoids. The looper complex of tea viz, *Buzura suppressaria*, *Hyposidra talaca*, *Hyposidra infixaria* and the bunch caterpillar, *Andraca bipunctata* were found to be parasitized by *Apanteles aristaeus*, *A. taprobanea*, *Sypiesis dolichogaster* and *Mestocharells javensis*. In the foot hills of Darjeeling, the braconids, *Cotesia* sp. and the tachinid, *Argyrochlyax* sp are important parasitoids of *Buzura suppressaria*. *Argyrochlyax* sp. could parasitise 42 per cent of *Euterusia magnífica*. Trichogramma, the egg parasitoids, has been widely used in sugarcane, rice, cotton and against the eggs of lepidopteran pests of tea. *Trichogramma dendrolimi* has been reported to parasitized the eggs of tea tortricids (Ishijima et al., 2008). In South India, *Erythmelus helopeltidis* Gahan parasitized the eggs of major tea pest *Helopeltis theivora* (Sudhakaran and Muraleedharan, 1998 and 2006)

1.3.5 Role of predator in biological control

The role of predators in the control of different agricultural insect pest had been reported earlier by various authors (DeBach and Hagen (1964), Henry (1979, 1985 and 1993), Bram and Bickely (1963) and Brooks (1994). In China to control citrus pest, biological control method have been used as an alternative means of chemical insecticides (Niu et al., 2014; Li et al., 2010; Luo et al., 2008; Yang and Wang, 2008). Use of predator as a biocontrol agent depends on its ability to locate
the target pest, high reproductive rate, adaptability and sustainability. For an effective biological control, the natural enemies always have to attacks only the target pest so that they do not affect the non target organism.

Tea plantations are regarded as highly suitable for biocontrol programme because of the type of climate, duration of crop, scale of planting and agronomic practices. It includes a wide variety of beneficial species which are common in most natural communities to maintain the minor status of many tea pests in tea ecosystem (Muraleedharan and Selvasundara 1995; Roy et al., 2014). Eighty species of predators, nine species of fungal and two species of bacterial pathogens have been recorded as natural enemies of RSM (Roy et al., 2014). Among the predators, phytoseiid mites, coccinellid beetles and their larvae and lacewings are dominant ones. From India 47 species of insects and mite had been recorded as predator and parasitoids of RSM (Muraleedharan et al., 2001; Das et al., 2010). Different types of predators such as Chrysoperla carnea, Oxyopes sp, Plexippus sp, Phidippus sp, Marpissa sp, praying mantids, reduviid bug plays an important role in suppressing the tea pests (Roy et al., 2005, Gurusubramanian et al., 2008; Hazarika and Chakraborti, 1998; Rahman et al., 2005b. Several species of coccinellids such as Cryptoconus bimaculatus, Juravia quandrinotata, J. opaca, Menochilus sexmaculatus and Stethorus gilvifrons, are present in the tea fields which feed on soft body arthropod pest like eriophyid mites, spider mites, and scale insects. Neoseiulus longispinosus Evans is a successful predator of O. coffeae in tea. Another important predators of O. coffeae are Oligota pygmaea Solier (Staphylinidae), Green lacewings (Neuroptera), Mallada boninensis Okamoto,
Mallada basalis Walker and Mallada desjardinsi Navas which play a key role to maintain the pest population. In southern India, the tea pests such as the mites, Acaphylla theae, Calacarus carinatus and Oligonychus coffeae; the thrips, Scirtothrips bispinosus; the aphid, Toxoptera aurantii; and the caterpillars, Caloptilia theivora, Homona coffearia and Cydia leucostoma are suppressed by a number of natural enemies (Muraleedharan et al., 1988). Aphids are serious agricultural pests of economic importance. Hippodamia (Adonia) variegata (Goeze) is an important natural enemy of aphids in many countries (Kontodimas and Stathas, 2005). For example, in Greece, H. variegata is one of the dominant predators (Kavallieratos et al., 2004; Kontodimas and Stathas, 2005; Karagounis et al., 2006) of Aphis gossypii Glover on cotton and Myzus persicae Sulzer on tobacco and peach trees.

1.3.6 Stethorini in biological control

Coccinellids are generally considered as the second largest group of predators of RSM. Cryptogonus bimaculatus, Jauravia quadrinotata, J.soror, J.opaca, Menochilus sexmaculatus and Stethorus gilvifrons are the common species of coccinellids in tea fields. The genus Stethorus are obligate predators of spider mites (McMurtry et al., 1970; Chazeau 1985; Rott and Ponsonby 2000; Ullah 2000) and several species have been reported to be effective bio control agents (Putman 1955a,b; Hull et al., 1977a,b; Tanigoshi and McMurtry 1977.,Gotoh et al., 2004; Mori et al., 2005). Their agricultural importance lies in their predation habits. Both adults and larval stages are voracious feeder of mite species. Forty percent of the reported species of Stethorus attacked spider mites of economic importance.
Approximately 90 species of *Stethorus* have been reported worldwide as predator of mite and several species have been reported as effective biological control agents (Putman 1955a; Hull *et al.*, 1977a, b; Tanigoshi and McMurtry 1977; Gotoh *et al.*, 2004; Mori *et al.*, 2005) of phytophagous mite in a diverse range of habitats, such as pome and stone fruits, brambles, tree nuts, citrus, avocados, bananas, papaya, palms, tea, cassava, maize, strawberries, vegetables, and cotton, as well as ornamental plantings, grasslands and forests (Biddinger *et al.* 2009). All the motile stages of *Stethorus* feed on different prey stages and have high host-finding capacity. The adults are long lived and have the potential to disperse a wide range. (Putman 1955; Tanigoshi and McMurtry 1977; Roy *et al.*, 2003, 2005). The ladybird beetle, *Stethorus gilvifrons* Mulsant, is one of the major predator of the RSM found in tea ecosystem. Adults and larval stages of *S. gilvifrons* predate randomly on the eggs, nymphs and adults of the RSM (Banerjee 1971, Roy *et al.*, 2014a). Another species of the genus called *Stethorus aptus* had been reported as a new predator of RSM for the first time (Babu, 2012) in Northeast India. Earlier this predator was found in citrus plant preying on *Panonychus citri* (McGregor) Li *et al.*, (1990). Tea pest complex is generally managed by the application of synthetic chemicals. However, some of the pesticides have toxic effect on predators leading to the mass destruction of natural enemies creating an ecological imbalance. Some of the insecticides are harmful to predators not only through their acute toxicity but also through persistent toxicity. Therefore toxic effect of pesticides has been recognized as one of the main pre-requisites for the establishment of effective integrated pest management programme.
1.4 Scope of the study

Red spider mite is one of the major pests of tea and extensive work has been done for its control measure but there is a lacuna on information related to the control of this serious pest by non chemical method especially through biological means. Recent survey conducted in the tea fields of Jorhat, Assam revealed the presence of a coccinellid predator, *Stethorus aptus* Kapur (Coleoptera : Coccinellidae) feeding on all stages of *O.coffeae*. Hence in the present study an attempt has been made to study the biocontrol potential of the predator to control RSM.

The predator *S. aptus* is a newly reported species of mite pest. Therefore studies on *S. aptus* in tea ecosystem desereves importance as a tool for assessing the possibility of the species to be a successful biocontrol agent of red spider mite. Seasonal dynamics study of the predator in tea plantations generates information on the abundance of *S. aptus* in different seasons. Detail study on predatory potential, functional response and optimum predator prey ratios and life history of *S. aptus* will help to implement this predator as a biocontrol agent for red spider mite.

1.5 Objectives

The main aim of the present study was to investigate the life history, feeding potential and toxic effects of insecticides on *S. aptus* in tea ecosystem. Keeping all these facts in view, the present investigation has been under taken with the following objectives:
• Evaluation of predatory potential of *Stethorus aptus* against Red spider mite

• Study of seasonal population dynamics of *Stethorus aptus* and its cooccurrence—in relation with abundance of Red spider mite and some abiotic factors

• Studies on lifecycle of *Stethorus aptus* under different seasons of the year

• Study the mass culture of *Stethorus aptus*

• Determination of pesticide tolerance level of *Stethorus aptus* to commonly used pesticides.