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REVIEW

Introduction of Non-native Predatory Mites for Pest Control and its Risk Assessment in Japan

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Abstract

The use of natural enemies instead of chemical pesticides has been increasing worldwide. Although non-native natural enemies are beneficial and commonly used as biological control agents, the risks of non-target effects caused by their release are of growing concern. Phytoseiid mites are a very common choice as introduced biological control agents. In Japan, 8 species of non-native phytoseiid mites, one of which is the same as the native type but originates from a non-native population, have been introduced for crop pest control. There is concern about the influence of the introduced phytoseiid mites on native phytoseiid mites that occupy a similar habitat, but very few risk assessments of these phytoseiid mites have been carried out in Japan. In this paper, we estimate the risks of the non-target effect caused by the release of these introduced non-native phytoseiid mites by using the risk indexes proposed by Mochizuki (2010), and briefly present the results of monitoring the species considered at risk from the release of non-natives.

Discipline: Insect pest
Additional key words: Acari, biological control, exotic natural enemy, non-target effect, phytoseiid mite

Introduction

Pest control is one of the key problems in agriculture. Although many natural and synthetic chemicals such as nicotine and DDT have been used to control crop pests, chemical pesticides have been shown to harm the health of living creatures, both animals and humans, while their repeated use results in pests becoming resistant. In 1889, the vedalia beetle, *Rodolia cardinalis* (Mulsant), was imported into California from Australia to control an invasive alien pest insect, the cottony cushion scale, *Icerya purchasi* Maskell, and successfully controlled the pest insects[3]. Since this success, using natural enemies as a form of biological control has gained global attention as a less harmful method than the application of chemical pesticides[36]. To control invasive alien pests, many natural enemies have been imported from the original country of the pests[36]. Releasing (augmenting) these natural enemies has also been performed to supplement any lack of natural enemies and to control pests inside greenhouses in their absence[36].

Recently, concerns have been raised that the import and release of non-native natural enemies may have non-target effects on native ecosystems[2, 32, 33, 36]. For example, a non-native lady beetle, *Coccinella septempunctata* L., was introduced into North America and released to control pest aphids on several crops, but after release, the native lady beetles, especially *C. transversoguttata richardsoni* Brown and *Adalia bipunctata* (L.), sharply declined and were partly displaced by the non-native lady beetle[9]. In 1996, the Food and Agriculture Organization (FAO) published a “Code of conduct for the import and release of exotic biological control agents,” sparking a global trend for the risk assessment of natural enemies prior to their import overseas[2, 32, 33].

Phytoseiid mites (Acari: Phytoseiidae) are a very common choice as biological control agents worldwide for controlling pest mites, thrips and whiteflies. As of 2003, more than 2000 species of phytoseiid mites had been reported globally, 85 of which were reported in Japan[8]. Phytoseiid mites are tiny: females are 0.3 to 0.6

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mm in length, but their predation activity is considerable[28]. Their reproductive rate is also high and comparable to that of prey species[27]. Therefore, they were examined as a biological control agent at an early stage, and promising species were exported and imported[36]. *Phytoseiulus persimilis* Athias-Henriot was introduced into Japan in 1966, for basic and applied research as a biological control agent for greenhouse horticultural pest insects, and was the first species to be registered as a biological pesticide[36]. Since the introduction of *P. persimilis*, several non-native phytoseiid mite species have been introduced and released in Japan (Table 1). New non-native phytoseiid mites are awaiting introduction and release into Japan, and the effective use of these new species, as well as those already imported, is being investigated. However, there has still been little investigation into the purpose of risk assessment of the non-target effect in Japan. In this paper, we estimate the risks of the non-target effect caused by the release of these introduced non-native phytoseiid mites by calculating their risk indexes as proposed by Mochizuki (2010)[21], and briefly present the results of monitoring the species considered at risk from the release of non-natives. We discuss the risks of releasing these introduced non-native phytoseiid mites and the role of risk assessment on these mites in terms of improving the risk assessment method.

Estimated risk of the non-target effect caused by the release of non-native phytoseiid mites

In Japan, the Ministry of the Environment announced its “Guidelines on Introduction of Environmental Impact Assessment of Biological Control Agents” in 1999[20, 36]. The Agricultural Chemicals Inspection Station performs an ecological risk assessment of non-native biological control agents following the guideline and makes decisions about their import and use[20, 36]. This guideline presents a stepwise procedure, and covers the important information needed for the risk assessment of non-native natural enemies[20, 36]. Mochizuki (2010)[21] pointed out, however, that this guideline is qualitative, and that a quantitative method such as that proposed in Europe by the EU-funded research project ERBIC (Evaluating Environmental Risks of Biological Control Introductions into Europe)[32] is needed. In the ERBIC method, the risk is evaluated by calculating the risk index, in which the scores of likelihood (probability) and magnitude (consequence) are multiplied in each assessment element, and the assessment element scores collectively totaled up. Mochizuki (2010)[21] arranged this method to be practical in Japan, where it was proposed as a new form of objective risk assessment. We summarize the method briefly, and estimate the risk index of already introduced non-native phytoseiid mites.

1. Risk assessment method proposed by Mochizuki (2010)[21]

First, risk index-1 is calculated by adding the scores of the three elements “establishment”, “dispersal” and “host range.” Each element score is calculated by multiplying the score of likelihood (L) and magnitude (M) (Table 2). Provided the risk index-1 doesn’t exceed 40, it’s decided that the risk is low, and the introduction of the species is permitted without further research. This cutoff line of a risk index-1 of 40 is based on the score of the vedalia beetle, which was introduced in 1911 to control the cottony cushion scale and has been established without unwelcome non-target effects in Japan. When the risk index-1 exceeds 40, it is decided that information on the risk is insufficient to grant permission for the introduction pending further research, and the total risk index must be calculated, whereby the scores of three additional elements, “direct effect on rare or endemic species,” “competition with native species” and “hybridization

Table 1. Phytoseiid mites introduced for biological control in Japan

	Phytoseiid mite	Target pests	Use in	[Introduction or registration] year
Commercially supplied (Augmentation)	*Phytoseiulus persimilis*	Spider mites	Greenhouse	1995
	Neoseiulus californicus	Spider mites	Greenhouse & Open field	2003
	Neoseiulus cucumeris	Thrips	Greenhouse	1998
	Iphiseius degenerans	Thrips	Greenhouse	2003
	Amblyseius swirskii	Thrips, [whiteflies]	Greenhouse	2008
Experimentally released (Classical biological control)	*Galendromus occidentalis*	Spider mites	Open field	1986
	Neoseiulus fallacis	Spider mites	Open field	1986
	Typhlodromus pyri	Spider mites	Open field	1986

with native species," are added to risk index-1. Provided the total risk index does not exceed 80, the introduction of the species is permitted but carefully, for example, accompanied with monitoring of the species. When the index exceeds 80, the introduction of the species should not be permitted without restriction, for example, the species may only be used in completely sealed greenhouses.

2. Risk index-1 of introduced non-native phytoseiid mites

The score of each element required in the risk index-1 calculation of introduced non-native phytoseiid

Table 2. Scores of likelihood (L) and magnitude (M) in six elements used to calculate risk index-1 and total risk index in Mochizuki (2010)[21]

L: likelihood

	Element					
	For the risk index-1			For the total risk index		
Score	Establishment	Dispersal[1]	Host range[2]	Direct effect on rare or endemic species	Competition with native species	Hybridization with native species
1	Cannot pass winter or summer	< 1 week	< 1 mm	Habitat and time; different from them	Not the same host range	No
2	One brood/year, non-diapause	1 - 2 weeks	1 mm - 3 mm	Very often the same habitat and time	Host range 10-30 % overlap	Low interspecific hybridization
3	Over two broods /year, non-diapause	2 - 3 weeks	3 mm - 5 mm	Partially overlapping habitat	50% overlap	High, sex ratio: not 50%
4	One brood/year, can diapause	3 - 4 weeks	5 mm - 10 mm	50% overlap	60-80% overlap	High, sex ratio: 50%
5	Over two broods /year, can diapause	> 1 month	> 10 mm	Always overlap	The same host range	Hybrid vigor

1: Longevity
2: Feeding amounts approximated by body length when introduced

M: magnitude

	Element					
	For the risk index-1			For the total risk index		
Score	Establishment	Dispersal[3]	Host range[4]	Direct effect on rare or endemic species	Competition with native species	Hybridization with native species
1	Local in Japan	< 10 cm/s	Genus	Does not eat rare/ endangered species	Even or inferior	Morphologically different
2	< 10% of Japan	10 - 50 cm/s	Family	Can eat species related to the rare one but cannot grow only with them	Coexistence with host	Uses different courtship signal
3	10 - 25%	50 cm/s - 1 m/s	Order	Does not prefer them in a choice test	Wins against 1-2 species	Females can mate many times
4	25 - 50%	1 m/s - 2 m/s	Class	Eats them and pest species equally	Wins against several species	Females mate only twice or three times
5	> 50%	> 2 m/s	Phylum or so	Prefers rare/ endangered species	Always wins	Females mate only once

3: Flight or walking speed of the introduced stage
4: Relationship with target species

mites was estimated as described below.

(1) Establishment

Likelihood. The phytoseiid mite is multivoltine. Experimentally introduced phytoseiid mites naturally enter a reproductive diapause in winter[26], but those commercially introduced are non-diapause species or strains[10, 26, 31, 35]. This is because these commercially introduced mites are often used for pest control in greenhouses, where non-diapause alien pest arthropods thrive, even in winter.

Magnitude. It is expected that experimentally introduced phytoseiid mites will be able to establish themselves all over Japan, due to their overwintering ability. Conversely, it is expected that commercially introduced phytoseiid mites will be able to establish themselves in southwestern Japan, since non-diapause *Neoseiulus californicus* (McGregor) has increased in orchards in central and southwestern Japan recently, replacing diapause *Neoseiulus womersleyi* (Schicha)[1, 10]. However, the recent increase of *N. californicus* has been dramatic (a phenomenon of the past 20-30 years[1]), and an artificial effect on the increase and range expansion is suspected[1, 10, 11]. Accordingly, further study would be necessary for attentive risk assessment.

(2) Dispersal

Likelihood. The longevity of the phytoseiid mite adult depends on temperature and food availability, but with their life history data in mind, phytoseiid mite adults of all species are expected to survive for at least three to four weeks[29].

Magnitude. Phytoseiid mites are small wingless arthropods with a walking speed of less than 10 cm/s[17]. However, aerial dispersal behavior after being drawn actively into the airstream was observed in several species of phytoseiid mites, including three that were experimentally introduced[4, 6, 12, 14]. While in flight, the mites can be dispersed over more than 100 m[16]. Although the mites cannot control their landing[15], this aerial dispersal might allow them to be dispersed at speeds greater than 2 m/s.

(3) Host range

Likelihood. The body of the phytoseiid mite is less than 1 mm, so its feeding amount is expected to be negligible in all species[8].

Magnitude. The commercially introduced species *P. persimilis* is a specialized predator of the *Tetranychus* species having a web structure[19]. The commercially introduced species *N. californicus* and two experimentally introduced species, *Galendromus occidentalis* (Nesbitt) and *Neoseiulus fallacis* (Garman), are selective predators of the tetranychid mites having a web structure, including *Tetranychus* species, hence the selective predators show a broader range for preying compared to the specialized predators[19]. Conversely, three commercially introduced species, *Neoseiulus cucumeris* (Oudemans), *Iphiseius degenerans* (Berlese) and *Amblyseius swirskii* Athias-Henriot, and an experimentally introduced species, *Typhlodromus pyri* Scheuten, are generalist predators that feed not only on target pests such as mites, thrips and whiteflies but also on coccids, honeydew and pollen[18, 19, 25, 34].

Table 3 shows the results of risk index-1 calculation in the introduced non-native phytoseiid mites. The risk indexes-1 of commercially introduced mites were under 40, and this result would support the appropriateness for permission for the introduction and release of commercially introduced mites. Conversely, the risk indexes-1 of experimentally introduced mites exceeded the cutoff point of 40, which indicates that their introduction should not have been permitted without caution or restrictions.

Monitoring of experimentally introduced non-native phytoseiid mites

Three non-native phytoseiid mites, *G. occidentalis*, *N. fallacis* and *T. pyri*, with resistance against pesticides, were introduced as agents to control pest mites in apple orchards from New Zealand to Aomori Prefecture, Japan, in 1986[24]. In several countries (e.g. New Zealand, Australia and North America), pesticide-resistant strains of these mites are effectively used as biological control agents in orchards combined with chemical control as Integrated Pest Management[13]. Part of the mite culture in Aomori Prefecture was transferred to Akita and Nagano prefectures, and the mites were experimentally released to control pest mites in apple orchards (Table 4)[22, 23, 24]. Increased numbers after release and the overwintering of *G. occidentalis* and *N. fallacis* were confirmed from 1987 to 1988 in Aomori Prefecture[24, 30], while those of *G. occidentalis* were confirmed from 1988 to 1989 in Akita Prefecture[22]. Their increases and overwintering in the orchards were regarded as positive, because the release of these introduced mites was conducted as an instance of classical biological control. Conversely, these mites are not currently used as biological control agents, and concern has arisen over the non-target effects on native phytoseiid mites caused by this release of non-native phytoseiid mites. To monitor the establishment of these mites and their effects on the native phytoseiid mites, Mochizuki et al. (2003, 2004, 2005) conducted a species composition survey of phytoseiid mites in these areas[22, 23, 24].

The surveys of *G. occidentalis, N. fallacis* and *T. pyri* were conducted in the season when pest spider mites and phytoseiid mites proliferated: August 2003 in Aomori Prefecture (11 years after the last release), August 2002 in Akita Prefecture (3 years after the last release) and

July 2004 in Nagano Prefecture (13 years after the last release). In Akita Prefecture, a supplemental survey was conducted in August 2007 (8 years after the last release), since a non-native mite, *G. occidentalis*, was found in the undergrowth of cherry and apple trees in Aomori Prefecture at least 8 years after the last release[24]. Leaves from apple, cherry, peach and willow trees were collected from the apple orchards where the non-native mites had been released and the surrounding areas. The existence of phytoseiid mites on these leaves was checked, and those found were prepared as slide specimens. The species were subsequently checked using phase microscopes and an identification table.

Figure 1 shows the results of the surveys. Non-native phytoseiid mites were not found in any of these three prefectures. The identified phytoseiid mites were *N. womersleyi*, *Typhlodromus vulgaris* Ehara, *N. calfornicus* and *Euseius finlandicus* (Oudemans). Unfortunately, it is not possible to compare the species composition before and after the non-native mite release, since no pre-release species composition surveys were conducted. However, all the mites identified were phytoseiid mite species commonly found in each area. Therefore, it appears that the non-native mites failed to establish themselves in these areas, or the effect on the native mites was negligible, even if they had established themselves there.

Many non-native mites were released in Aomori and Akita prefectures (Table 4), and their proliferation after release and overwintering were confirmed in both prefectures. Why did these non-native mites (resistant to pesticides) fail to establish themselves in these areas? One possible explanation is exclusion by the native phytoseiid mites[24]. There are reports that *G. occidentalis* is often displaced by other phytoseiid mites because of its

Table 3. The risk index-1 of the introduced non-native phytoseiid mites as calculated by the risk assessment method proposed by Mochizuki (2010)[21]

	Species		Establishment	Dispersal	Host range	Risk index-1 (Total)
Commercially introduced (Augmentation)	*P. persimilis*	L	3	4	1	
		M	4	5	1	
		L×M	12	20	1	33
	N. californicus	L	3	4	1	
		M	4	5	2	
		L×M	12	20	2	34
	N. cucumeris	L	3	4	1	
		M	4	5	5	
		L×M	12	20	5	37
	I. degenerans	L	3	4	1	
		M	4	5	5	
		L×M	12	20	5	37
	A. swirskii	L	3	4	1	
		M	4	5	5	
		L×M	12	20	5	37
Experimentally introduced (Classical biological control)	*G. occidentalis*	L	5	4	1	
		M	5	5	2	
		L×M	25	20	2	47
	N. fallacis	L	5	4	1	
		M	5	5	2	
		L×M	25	20	2	47
	T. pyri	L	5	4	1	
		M	5	5	5	
		L×M	25	20	5	50

less competitive ability, but it is often dominant in intensively sprayed sites[5]. In Aomori Prefecture, spraying of pesticides was reduced after the release of these introduced mites[24]. If native phytoseiid mites were excluded by pesticide spray, these introduced mites might have had the opportunity to occupy these orchards.

Conclusion

The estimated risk indexes-1 suggest the need for further assessment in experimentally introduced phytoseiid mites and that they should not have been released without caution or restriction (Table 3). However, in the species composition surveys performed to monitor these

Table 4. Release records of the non-native phytoseiid mites into apple orchards[22, 23, 24]

(a) Aomori Prefecture

Year	Month	Site	Mite Species	Number
1986	Aug.-Sep.	Field 1	*G. occidentalis*	1,100
			N. fallacis	1,000
1987	July	Field 1	*G. occidentalis*	420
1988	May	Field 2	*N. fallacis*	No description
1989	June-July	Field 1	*G. occidentalis*	No description
			N. fallacis	No description
			T. pyri	No description
1990	May, Aug.	Field 1	*T. pyri*	400
1991	June-July	Field 1	*G. occidentalis*	140
			N. fallacis	140
			T. pyri	No description
1992	July	Field 1	*G. occidentalis*	1,500
			N. fallacis	176,000

(b) Akita Prefecture

Year	Month	Release site	Mite Species	Number
1988	June-Aug.	Field 3	*G. occidentalis*	5,000
1989	June-Aug.	Field 3	*G. occidentalis*	4,000
1990	July	Field 4	*G. occidentalis*	1,000
1990	Aug.	Field 5	*G. occidentalis*	1,200
1992	July-Aug.	Field 6	*G. occidentalis*	2,600
1996	July-Aug.	Field 7	*G. occidentalis*	No description
1997	July	Field 7	*G. occidentalis*	No description
1999	July	Field 7	*G. occidentalis*	No description

(c) Nagano Prefecture

Year	Month	Release site	Mite Species	Number
1990	July	Field 8	*G. occidentalis*	3,150
1991	July	Field 8	*G. occidentalis*	2,150

Field 1 & 2: Apple orchards in Aomori Apple Experiment Station (Kuroishi)
Field 3: Apple orchard in Akita Fruit-Tree Experiment Station (Kaidoshita, Hiraka)
Field 4: Apple orchard in Sawaguchi, Masuda
Field 5: Apple orchard in Akesawa, Masuda
Field 6: Apple orchard in Hansuke, Masuda
Field 7: Apple orchard in Tokufuji, Inagawa
Field 8: Apple orchard in Nagano Fruit Tree Experiment Station (Suzaka)

experimentally introduced phytoseiid mites several years after their release, these mites were not found, and there were no causes for alarm in terms of the species composition (Fig. 1)[22, 23, 24]. Therefore, Mochizuki et al. (2003, 2004, 2005) concluded that no serious non-target effects on native phytoseiid mites would be caused by the release of these experimentally introduced mites[22, 23, 24].

Conversely, the risk index-1 of commercially introduced mites was under the cutoff of 40 (Table 3), which indicates no need for further assessment regarding permission for their introduction. However, there are recent suspicions that these commercially introduced phytoseiid mites might have established themselves in Japan and affected the native phytoseiid mites. For example, when estimating the score of these species for the "establishment" element, we referred to the recent dramatic increase of *N. californicus* in central and southwestern Japan, replacing *N. womersleyi*[1]. *N. californicus* has been in Japan since before the introduction of its non-native strain[7], but it was naturally suspected that the dramatic increase of *N. californicus* replacing *N. womersleyi* was caused by the widespread use of commercially introduced *N. californicus.* The factors behind the dramatic increase of *N. californicus* replacing *N. womersleyi* were investigated from the perspectives of pesticide susceptibility, cold hardiness and genetic diversity in native and commercially introduced strains of *N. californicus* and the native *N. womersleyi*[1, 10, 11]. The results of these studies suggest it is unlikely that the widespread use of the introduced strain of *N. californicus* was the main factor in the disappearance of *N. womersleyi*. However, the reason for the disappearance remains unclear, and the involvement of commercially introduced *N. californicus* has not been completely ruled out.

We consider it wise to perform further assessment of commercially introduced non-native phytoseiid mites, which would help clarify their risks and reduce unnecessary suspicions. In addition, the further assessment would be useful for improving the risk assessment method. The history of natural enemy introduction, especially commercially, is still short in Japan, hence the lack of data concerning the influence of repeated releases over

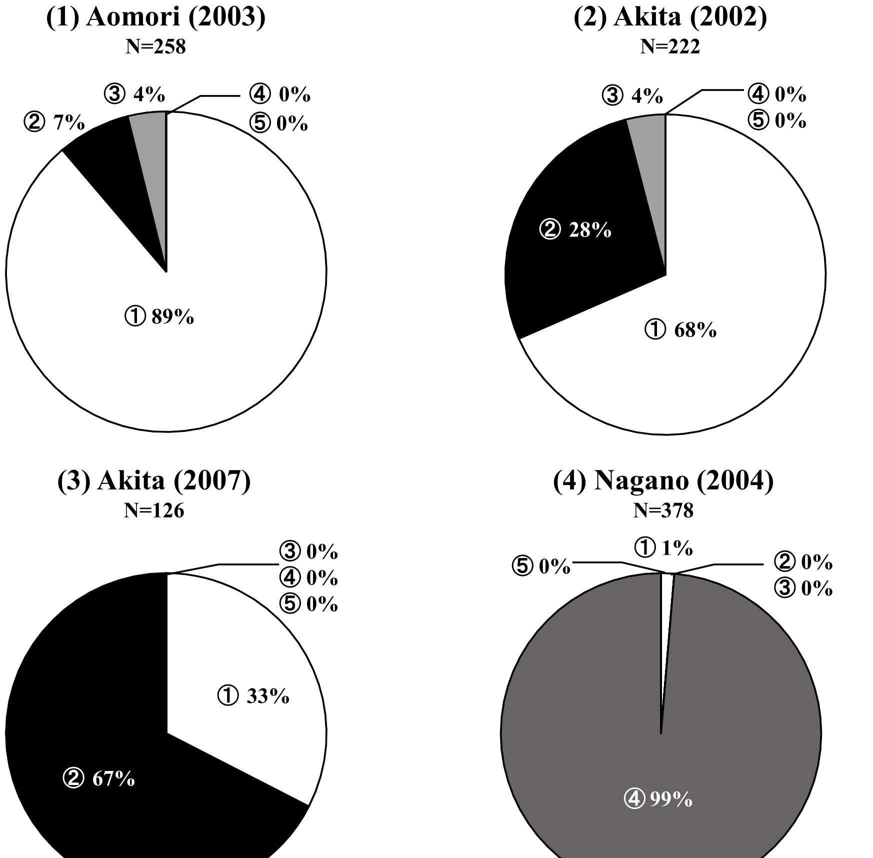

Fig. 1. Species composition of female phytoseiid mites in surveys conducted in (1) Aomori, 2003[24], (2) Akita, 2002[22], (3) Akita, 2007 (Sato et al. unpublished data) and (4) Nagano, 2004[23]

□ : ①*T. vulgaris,* ■ : ②*N. womersleyi,* ■ : ③*E. finlandicus,* ■ : ④*N. californicus,* ▨ : ⑤Non-native mite.

an extended period. We have to continue improving the risk assessment method using newly gathered data. These phytoseiid mites are good for this activity, since they were commercially introduced into Japan early, and their amount and the number of species involved has been increasing year by year. Introduced non-native natural enemies are mainly used to control invasive alien pest arthropods, which carry much greater risks than non-native natural enemies. Therefore, we must be prudent, not only in permitting but also rejecting the introduction of non-native natural enemies. To avoid granting permission without due consideration as well as excessive rejection, study including perspectives of the effective use as biological control agents and the risk assessment of non-target effects in non-native phytoseiid mites would be important.

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