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Review article

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Abstract

The identity, geographical distribution, and host range of codling moth is reviewed, and the evidence for sweet cherry being a host is critically analysed. A model is described which assesses the risk of codling moth being spread through international trade in sweet cherries, as exemplified by exports from, respectively, New Zealand and USA to Japan in winter and summer. The model is based on the recorded incidence of codling moth in cherries and its estimated probability of survival during storage, transport to, and arrival in Japan, using data from specific studies and from wider knowledge of the phenology, life history, and biology of the species. There is unambiguous experimental evidence, supported by field observations, that sweet cherry is not a host of codling moth. It is concluded that the risk of codling moth establishing in an overseas country such as Japan through the cherry trade is extremely low and that specific quarantine measures to prevent the introduction of this insect by this route are not technically justified. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Codling moth; Cherry; Risk analysis; Quarantine

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1. Introduction

The origins and distribution of the sweet cherry, *Prunus avium* L. (*Prunus sylvestris* Ray or *Cerasus avium* L. (Moench)), were described by Webster and Looney (1996). It is indigenous to parts of Asia, including northern Iran, the Ukraine, and other countries south of the Caucasus, and is considered to have originated in the area of the Caspian and Black Seas. It has become naturalized throughout Europe from southern Sweden to the Mediterranean, and is now found wild in many countries, including northern India and the southern plains of Europe. The available evidence indicates that the area of origin of codling moth, *Cydia pomonella* (Linnaeus), is also Eurasia, linked to the distribution of large-fruited apples (*Malus* spp.) in western Asia, eastern Europe, and southwestern Siberia, to pear, *Pyrus communis* L., in the Caucasus, and to walnut, *Juglans regia* L., in the Caucasus and Turkestan (Barnes, 1991). With the overlapping areas of origins and spread of codling moth (see the section on Geographical distribution) and sweet cherry, there have been many thousands of years in which this insect and sweet cherry have co-existed, providing the opportunity for the evolution of a host association, but this has not occurred. For instance, Webster and Looney (1996) point out that sweet cherry was known in Albania long before the foundation of the great hellenic civilisation in Greece, yet they do not list codling moth among the pests of sweet cherry.

Despite this, occasional records of codling moth larvae in sweet cherry fruits have led to quarantine restrictions which have hampered international trade in sweet cherries. Sweet cherries shipped to Japan from Canada, USA, or New Zealand must undergo pre-export fumigation with methyl bromide (Gaunce et al., 1981; Maindonald et al., 1992; Moffitt et al., 1992). This requirement is based on the classification of sweet cherry as a host of codling moth, but it is our view that there is strong scientific evidence to the contrary and that the risk of codling moth being distributed through international trade in sweet cherries should be assessed. This paper reviews the world literature on the host status of cherry for codling moth, assesses the risk of codling moth occurring in export sweet cherries in the absence of fumigation, and models the potential risk of establishment in Japan following shipment from USA and New Zealand.

1.1. Codling moth

1.1.1. Taxonomy and nomenclature

The codling moth, *Cydia pomonella* (Linnaeus), has a long and complex taxonomic history that includes cases of synonymy and homonymy, and a controversy in usage that led to a petition to the International Commission of Zoological Nomenclature. As would be expected given its history, both the systematic and economic literature are replete with different names for this animal, the most common of which are *Carpocapsa pomonella*, *Laspeyresia pomonella*, and *Cydia pomonella*. Brown (1979) presented a detailed review of the various name changes; the most important are summarized below.

1.1.1.1. The specific epithet. The codling moth was first described from Europe by Linnaeus (1758) as *Phalaena Tinea pomonella*. It subsequently was described by other early European authors: *Phalaena aeneana* Villers and *Carpocapsa putaminana* Staudinger (see Table 1 for complete synonymy). The relatively short list of synonyms is a reflection of the fact that the species exhibits little variation in color and pattern. As the senior synonym, the specific epithet "*pomonella*" has priority and is the correct species name.

Table 1
Specific synonymy of *Cydia pomonella*

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pomonella (Linnaeus 1758) (*Phalaena*)
  pomonana (Denis and Schiffermüller, 1776) (unjustified emendation)
  pomana (Fabricius, 1793) (*Pyralis*) (unjustified emendation)
  aeneana (Villers, 1789) (*Phalaena*) (synonym)
  putaminana (Staudinger, 1859) (*Carpocapsa*) (variety)
  simpsoni Busck, 1903 (subspecies)

1.1.1.2. The generic name. In nearly all the economic and taxonomic literature from about 1830 to about 1960 (e.g., Busck, 1903; Simpson, 1903a, b; Barnes and McDunnough, 1917; Newcomer and Whitcomb, 1924; Forbes, 1924; MacKay, 1959; and many others), the codling moth is referred to as *Carpocapsa pomonella* (L.). During this time, at least three authors (i.e., Walsingham, 1897, 1914; Fernald, 1902; Pierce and Metcalfe, 1922) used *pomonella* in combination with the genus *Cydia* (i.e., *Cydia pomonella*), but this combination apparently did not receive widespread support or usage. Obraztsov (1959) considered *Carpocapsa* Treitschke, 1829 and *Cydia* Hübner, 1825 to be junior synonyms of *Laspeyresia* Hübner, 1825. The result was that from about 1960 through about 1980, codling moth most commonly went under the name *Laspeyresia pomonella*. In the 1970s it was realized that the genus *Laspeyresia* had been used prior to Hübner's (1825) description as a misspelling of *Laspeyria* Germar, 1810, a genus in the Noctuidae (Lepidoptera) (R.L., 1817); hence, according to rules of nomenclature the name is "unavailable" for use in the Tortricidae. Accordingly, the next available name for *pomonella* is *Cydia*, which should be the correct generic name.

1.1.1.3. Familial assignment. *Cydia*, along with its various synonyms, historically had been considered a member of the Olethreutidae; Heinrich (1926) treated it as a member of Laspeyresiinae, a subfamily of Olethreutidae. By the 1960s (e.g., MacKay, 1962; Powell, 1964), the concept that Olethreutidae and Tortricidae were more appropriately referred to as a single family (Tortricidae) had become widely accepted. Under current concepts (Horak, 1999), *Cydia* and related genera are included in the tribe Grapholitini (or incorrectly Laspeyresiini) of the Olethreutinae (Tortricidae).

1.1.2. Description and diagnosis

1.1.2.1. Description of adult. With a forewing length of 14–22 mm, *Cydia pomonella* is a moderately small tortricid moth. The forewing is entirely suffused or overscaled with pale maroon-brown, slightly darker in the basal one-third, with a pattern of indistinct, transverse striae. There is an indistinct purplish brown "eye-spot" edged with copper or gold scales in the tornus of the forewing. The hindwing is pale gray; the male has a unique fold along the basal two-thirds of the cubital vein from which a hairpencil of long sex scales arises. For illustrations see Simpson (1903a), Bradley et al. (1979) and Covell (1984).

1.1.2.2. Diagnosis of adult. Adults of the codling moth can be confused with several other species, all of which are in the tribe Grapholitini. Although somewhat similar to several species of *Grapholita* that are pests of *Malus*, *Pyrus*, and *Prunus* (e.g., *G. molesta* (Busck), *G. funebrana* (Treitschke), *G. prunivora* (Ragonot)), *C. pomonella* is most similar to dark specimens of *C. splendana* (Hübner) (usually associated with Fagaceae) on the basis of overall size and forewing pattern. *C. pomonella* can be distinguished from the *Grapholita* species by its larger size. It can be separated from all similar species by the presence of the distinct patch of slender, elongate sex scales that arises in a moderately deep fold of the cubital vein of the hindwing of the male. The male and female genitalia also are distinct but dissections are necessary to distinguish the structures; for illustrations see Pierce and Metcalfe (1922) and Heinrich (1926).

1.1.2.3. Description of larva. MacKay (1959) presents a detailed description and illustrations of the larva. Last instars are 15–19 mm in length, moderately stout, and have a pale body colour with moderately large pinacula. The head is yellow brown, often overlaid with a darker brown pattern. The anal and prothoracic shields are yellow, both with a moderately distinct pattern of pale brown spots and specks. The chaetotaxy (arrangement of setae) is typical of other olethreutines. The anal fork is absent.

1.1.2.4. Diagnosis of larva. The larva of *C. pomonella* can be distinguished from most *Grapholita* pests of *Malus*, *Pyrus*, and *Prunus* (e.g., *G. molesta, G. funebrana, G. prunivora, G. packardi* Zeller) by the absence of the anal fork. The larva is most similar to that of *C. splendana*, but usually can be separated by its darker distinct pattern of brown dots and specks on the prothoracic and anal shields, and the presence of 25–35 crochets on the anal prolegs in comparison with 15–20 for *C. splendana*. *C. splendana* usually attacks *Castanea*, *Quercus*, and other Fagaceae, rather than the fruit of *Malus*, *Pyrus*, *Prunus*, and other Rosaceae. Because the position and number of setae may vary between individuals, unequivocal identification is sometimes difficult.

1.2. Geographical distribution

The codling moth now occurs in the temperate regions of all major continents. Its worldwide distribution is detailed in Map No. 9 of the CAB International Series A "Distribution maps of pests" and in the associated

country list (CAB International, 1995). It is present in both the eastern and western states/provinces of USA and Canada, in Mexico, and in the pome fruit growing regions of a number of South American countries. It is widespread throughout Europe north to southern Scandinavia and eastward to Siberia, to north India, and to Xinjiang and Gansu in China. It is widely established in Africa and occurs on a number of islands, such as Madeira, Canary Islands, and Mauritius. It has also reached the fruit growing regions of Australia and New Zealand, except that eradication campaigns have prevented its permanent establishment in Western Australia (e.g., Anonymous, 1993).

The codling moth has demonstrated an ability to colonize apple and pear trees wherever the climate is suitable for their commercial production. The outstanding area not yet colonised by codling moth, but suitable for its establishment, is Japan, especially its pome fruit growing regions. If it were to establish there, it could be expected to be a major pest of apples and pears, comparable in importance to its status in other parts of the world, which is well documented (e.g. Barnes, 1991). Compared to Japan, the situation of codling moth in the Russian Far East is less clear, since Shel'deshova (1967), a codling moth specialist, reported finding codling moth caterpillars in 1958 and 1959 at Khabarovsk in crab apples and beneath the bark of an apple tree. He further reported (Shel'deshova, 1967) finding codling moth at several points in the Southern Primor'ye as far as Vladivostok and concluded that colonisation of the Far East horticultural areas was taking place. He also concluded that the insect was likely to colonise the milder climate in the fruit growing regions of the Korean Peninsula. However, since that time there have been no reports of codling moth in Korea (e.g., Byun et al., 1998). On the other hand, it is clear that codling moth is moving eastward in China because it is now reported (China Agriculture Press, 1994) from Qinghai, Ningxia, and Shanxi in addition to Xinjiang and Gansu.

A major historical contributor to the spread of codling moth has been human migration and movement along the transport routes of the world. Apple trees and associated codling moth were transported by colonists from Europe to many countries, particularly during the 19th century. In addition, apple tree seedlings (probably originating from the seeds in discarded apple cores) are scattered along overland road and rail routes, and these trees have provided staging posts for the widespread establishment and distribution of codling moth.

The transport of infested apple fruits and apple trees is recognised historically as the primary means of distribution of codling moth around the world. In contrast, there are no records of sweet cherry fruits or trees being responsible for the spread of codling moth to new locations, even now that the transport of infested apple fruits and/or trees has ceased to be a major pathway.

1.3. Host range and adaptability

Codling moth is oligophagous and most host plants are in the family Rosaceae. An exception to this is walnut, *J. regia* L., which is heavily attacked by codling moth in some localities (Boyce, 1935; Michelbacher and Ortega, 1958). Other unusual fruits which have been reported to be infested in the field but which are not known to sustain codling moth populations (i.e., not true hosts) are hawthorn (*Crataegus* spp.; Rosaceae) (Bieberdorf, 1956; Chapman and Lienk, 1971), melon (*Cucumis melo* L.; Cucurbitaceae) (Adkin, 1931), and madroño (*Rheedia madruno* (H.B.K.) Planch and Triana; Guttiferae) (Garces and Gallego, 1947). Wellhouse (1920) considered that most, if not all, reports of codling moth from hawthorn were misidentifications of *G. prunivora*. Similarly, Putman (1963) questioned the authenticity of codling moth records from orange, *Citrus sinensis* (L.) Osbeck, and persimmon, *Diospyros virginiana* L.

1.3.1. Pome fruits

Codling moth is known worldwide as a primary pest of apples, *Malus domestica* Borkh. and pears, *P. communis* L. (see the section on Geographical distribution), and fruits damaged by the codling moth are unmarketable. In stark contrast to sweet cherry trees (see below), damage of 30–80% occurs widely on neglected apple and pear trees, despite the presence of natural enemies. A primary reason for this is that the ovipositing female lays her eggs singly and at random with respect to fruits (Wood, 1965), distributing her eggs on or close to many different apples or pears within the tree. Moreover, once the codling moth larva has located and entered a fruit, it is well protected from natural enemies during its development. All cultivars of Asian pear, *Pyrus pyrifolia* Nakai, grown in California are hosts for the codling moth (Barnes, 1991). Quince, *Cydonia oblonga* Miller, may be attacked by the codling moth, especially when adjacent to apple or pear orchards with high infestations (Bieberdorf, 1956; Barnes, 1991).

1.3.2. Stone fruits

Sweet cherry will be discussed in the next section. Codling moth infestations in stonefruits were presumed initially to have come from neighbouring apple and pear orchards (Smith, 1940). However, research has shown that codling moth is a pest of some stonefruits, even when these are isolated from pome fruit orchards.

Codling moth can be a serious field pest of plums (including damsons and prunes), *Prunus domestica* L. and *Prunus salicina* Lindl. (Strand, 1999), but is more often only a very minor pest of these crops (Zech, 1958). *P. domestica*, the European plum, and the damson, *P. insititia* (L.) Bullace, seem to be more resistant to codling moth infestation than *P. salicina*, the Asian plum (Barnes, 1991). Apricots, *Prunus armeniaca* (L.), are also

Table 2
Certified sweet cherry exports and inspections in western USA and the numbers of codling moth found (PNW = Pacific NorthWest)

Year	No. of certified cartons shipped		No. of cherries inspected ($\times 10^3$)		Codling moth	
	PNW	California	PNW	California	PNW	California
Japan and Korea[a]						
1978	133,192		14,918.4		0	
1979	232,868		26,080.0		0	
1980	290,795		32,569.6		0	
1981	313,995		35,167.4		0	
1982	193,982		15,518.4		0	
1983	172,744		13,819.2		1	
1984	210,494		16,840.0		0	
1985	187,933		15,035.0		0	
1986	454,518		33,478.4		0	
1987	932,181	221,077	44,745.6	9550.5	0	1
1988	573,579	406,562	27,532.8	17,563.5	0	0
1989	615,170	392,294	29,528.0	16,947.1	0	0
1990	414,099	393,103	19,876.8	16,982.0	0	1
1991	380,541	277,937	18,266.0	12,006.9	0	1
1992	728,230	730,491	34,955.0	31,557.2	0	2
1993	743,083	751,923	35,668.0	32,483.1	0	1
1994	737,005	996,390	35,376.2	43,044.0	0	0
1995	754,638	664,278	24,148.4	19,128.4	0	0
1996	572,695	751,536	18,326.2	21,755.4	0	1
Subtotal	8,641,742	5,585,591	491,849.4	221,018.1	1	7
Japan[b]						
1997	545,288	898,942	6870.6	16181.0	0	4
1998	506,140	315,704	6377.4	5682.7	0	0
1999	692,730	1,151,948	8728.4	20,735.1	0	0
Subtotal	1,744,158	2,366,594	21,976.4	42,598.8	0	4
Total	10,385,900	7,952,185	513,825.8	263,616.9	1	11

[a] Years 1978 to 1996 from Moffitt (1997) who estimated 80 cherries/lb. PNW exports 20 lb. cartons and California 18 lb cartons.
[b] Years 1997 to 1999 are records from USDA-APHIS and Northwest Fruit Exporters (Yakima, Wash.) using an estimate of 63 cherries/lb for PNW and 100 cherries/lb for California. 1% of export cartons were inspected in this period.

heavily attacked by codling moth in some parts of the world (Pettey, 1925; List and Yetter, 1927; Bovey, 1949; Madsen and Borden, 1954). The levels of reported damage by codling moth to peaches, *Prunus persica* var. *persica*, and nectarines, *Prunus persica* var. *nucipersica* (Suckow) C.K. Schneid (Nagy and Jermy, 1972; Smith, 1940; Strand, 1999), are lower than its incidence in plums and apricots. Hagley et al. (1980) attributed the failure of forced oviposition on peach fruit in the laboratory to the dense hairs on the surface. Moreover, only one-third instar codling moth was found when 37,908 culled California nectarines were examined for codling moth (Curtis et al., 1991). Later, Curtis et al. (1992) collected three-fourth instars from 108,000 nectarines and concluded this fruit was a non-preferred host (see also below). Soft-shelled cultivars of almond, *Prunus dulcis* (mill.) D.A. Webb, may be infested from nearby apples and pears (Barnes, 1991).

Hagley et al. (1980) concluded that the leaves and fruits of sour cherry, *Prunus cerasus* L., were unattractive as oviposition sites; they added that codling moth had not

been recorded from sour cherry during eight years of survey work at their research station.

1.3.3. Sweet cherry

Recent laboratory and field studies demonstrate that codling moth has severe difficulty completing its life cycle on sweet cherries and seriously challenge the classification of sweet cherry as a host of codling moth (Hansen et al., 1999; Wearing and McLaren, 2001; and see below). This research supports the view of Barnes (1991) that evidence is lacking that codling moth populations can be maintained in sweet cherry orchards. Codling moths are not an economic pest of sweet cherries (Yarris, 1976; Webster and Looney, 1996), and the primary resource manual for orchard control in the Pacific Northwest of USA does not include codling moth as a pest of sweet cherries (Beers et al., 1993). There is evidence from cherry export inspections in the USA that codling moth occurs in cherry fruits at **extremely** low levels (see Table 2). However, the combination of this rarity with the non-preference for, and poor development

of, codling moth on sweet cherry (see below) calls into question all early reports that sweet cherry is a host of codling moth.

Mote (1926) reported "codling moth-like larvae" in cherries from Oregon and a small number were reared through and identified as codling moth. Losses to the cherry growers in the state from these larvae were described as negligible, and the infestation rates quoted (1–4% and 4–10%) referred to samples from individual trees. This limited record indicates that only a few larvae were reared, and it is impossible to determine what proportion of the "codling moth-like larvae" were in fact codling moth. Such damage has not been observed in Oregon since. List and Yetter (1927) reported rearing codling moth from boxed cherries, but this host association is in doubt because it is unclear if infestation occurred on the trees in the field. Mackie (1931) recorded the occurrence of codling moth in Californian cherries during a field survey but provided no supporting description or verification. Madsen and Borden (1954) mentioned control programs against codling moth in cherries, but did not give any data to justify these procedures, which therefore appear to have been prompted by the earlier quoted reports. Apart from these three early records, there is no more recent evidence to show that sweet cherry is a host of codling moth. For example, microscope inspection of 6400 cherries from 30 growing areas in Washington State, USA, found no codling moth (Rehmke et al., 1998) (and see specific studies described below). A report of damage to cherries in Germany was found not to be due to codling moth (as originally thought) but caused by *G. funebrana* (Lehmann, 1966). Similarities among the larvae of codling moth and related species almost certainly has contributed to some early records of codling moth in cherries (and see the Section on *Diagnosis of larva* above).

1.3.4. Adaptation to new hosts

Codling moths primarily attack rosaceous fruits. However, the English walnut, *J. regia* L. (Juglandaceae), is a major codling moth host, and wild walnuts, which share its region of geographical origin with apple, are attacked by codling moth (Barnes, 1991). In California, walnuts are grown in extensive plantations, much larger than traditional apple and cherry orchards, and these large agricultural monocultures provide reproductive isolation suited to specific host adaptation by new pests. Quayle (1921) discussed the life history of codling moth on California walnuts. Here larvae overwinter in the loose bark of walnut trees; the next brood of larvae attack the nut at the calyx end until the shell hardens; and there may be a partial third generation. When the shell is too hard for the larvae to penetrate, they feed on the adjacent husk and sometimes enter through the shell suture. Codling moths that attack walnuts are believed to be a separate race, and a genetic component of host

preference between apple and walnut has been demonstrated (Phillips and Barnes, 1975).

Philips and Barnes (1975) also discovered that larval diapause occurs earlier in codling moths that develop on plum than in those feeding on either walnut or apple. They concluded that a distinctive host race of codling moth has formed on plum in California, with origins from walnut-feeding populations. Its distribution is restricted, and in Canada over an eight-year period, no codling moths were collected from a plum orchard although they were recovered from a nearby apple orchard (Hagley et al., 1980). There is also evidence that, when apricot orchards are isolated from other host trees, codling moths may form races specific to apricots (Barnes, 1991).

We have found no reported cases of codling moth developing a race specific to sweet cherry. Despite thousands of years of coexistence of sweet cherry and codling moth in Eurasia, codling moth has not become a pest of this crop (Webster and Looney, 1996), as confirmed by a recent extensive survey in Turkey (Ozbeck et al., 1996).

2. Factors affecting the risk of codling moth in sweet cherry before and during shipping

The extremely rare incidence of codling moth in sweet cherries has raised the question whether sweet cherry is a host of codling moth. Although many insects have a range of host plants on which they develop and reproduce successfully, there are often other plants on which they occasionally feed and may be recorded. Some of these plants are not hosts because they do not permit development and survival of a population of the insect under natural conditions. This depends on a complex series of interactions between the insect and the plant in the field, including selection by adult and larval stages, establishment, feeding and development, mortality of different stages, and adult reproduction and fecundity. We here discuss aspects of the relations of codling moth with sweet cherry.

2.1. Host plant preference and cherry – specific studies

Research in New Zealand, conducted in 1995–96 and 1998–99, investigated the preference of codling moth for sweet cherry in the field (Wearing and McLaren, 2001). In the first experiment, individual bearing sweet cherry, nectarine, and apple trees were interplanted in a complete randomised block design using six replicates. No sprays were applied to the trees. The trial site was exposed to natural emergence of adult codling moths over the spring and summer, and the oviposition preferences of the moths were investigated. Hatching larvae were able to feed and develop on the plants selected by the adult moths, or to disperse elsewhere (see Wearing and

McLaren, 2001 for full details). Sampling of foliage and fruits failed to detect a single egg or larval entry on the cherries, whereas both were found on all the apple trees by mid-December (early summer), leading to heavy crop damage (average = 37%) at harvest. This experiment demonstrated unequivocally the non-preference of codling moth adult females for sweet cherry or nectarine in the presence of neighbouring apple trees, when all three were offered to the insect for oviposition in the field. This occurred despite high levels of crop infestation resulting on the apple trees alongside (4.5 m) the sweet cherry trees. Any larvae that dispersed after hatching also affected only the apples.

Similar results were obtained in the second experiment in which codling moth infestation of fruits was recorded in replicated blocks of unsprayed sweet cherries and apples adjacent to each other, or nearby (within 100 m, see the section on Dispersal) (Wearing and McLaren, 2001). Pheromone trapping showed very high numbers of codling moth males in most of the apple blocks and that lower numbers were trapped in the nearby cherry blocks. Total crops of sample cherry and apple trees were inspected for codling moth larvae, eggs, and damage. High levels of damage were found in most of the apple blocks (average = 35%, range 3.5–92.2%). In contrast, no codling moth eggs, larvae, or their damage were found in any of the 89,000 sweet cherries examined. The close proximity of the pipfruit and cherry trees at the sites did not result in cherry infestation, despite the occurrence of multiple entries by larvae on the neighbouring apples. The absence of codling moth in the sweet cherries was supported by the results from banding the trunks with corrugated cardboard. No codling moth larvae were recovered in any of these bands, whereas previous research on pear trees has shown a strong relationship between the numbers of larvae which completed development in the fruits and the numbers of larvae found in bands on the same tree (Wearing and McLaren, 2001).

Both these experiments were conducted under conditions where high densities of codling moth were free to attack sweet cherries in the absence of insecticides. The results seriously challenge the classification of sweet cherry as a host of codling moth.

2.2. Development on cherry – specific studies

In several laboratory studies, single newly hatched codling moth larvae were allowed to infest individual cherries of different cultivars and maturity levels, and development was observed to the adult stage (Hansen, 1999b; Hansen et al., 1999). Except for the first instar, identifying individual instars was difficult. Considerable size variation was observed among the larvae. Head capsule widths are not a reliable character to determine instar because of the effect of food resource, temperature, and intraspecific competition (Hathaway et al., 1971;

Williams and McDonald, 1982; Ferro and Harwood, 1973). Mature larvae were recognized by their brown colour and markings on the head capsule and by their ability to spin cocoons. Larvae took appreciably longer to reach the pupal stage, and mature larvae were often significantly smaller than those from the laboratory colony reared on apples. Adult emergence of moths that developed on cherries ranged from only 1 to 5.6% on the major export cvs "Bing", "Rainier" and "Van", and up to 16% on the minor cv. "Chelan" (Hansen, unpublished).

To determine whether codling moths can develop on cherries in the field, five cherry trees with abundant fruit were caged in an experimental orchard in Moxee, Washington and 500 adult moths (a 1 : 1 sex ratio was assumed) were released in each cage (Hansen et al., 1999; Hansen, 1999a; Hansen and Rehmke, in prep.). Caged apple trees were infested in a similar manner and used as controls. Eggs on fruits were counted, and larval development and fruit condition were recorded weekly. The cages protected the eggs and larvae from natural predators and parasites on the trees and in the ground cover, and this may have enhanced their survival. Most of the larvae did not remain in the fruits on the tree, but were found in aborted fruits on the floor of the cages. Larval development in cherries was much slower than that which occurred in apples in the laboratory or on rearing diet, and larvae were frequently smaller than colony-reared larvae of the same developmental stage. These are similar results to those observed in larvae reared on cherries in the laboratory (Hansen et al., 1999). Pooling the data from all cherry cages, nine cocooned larvae were recovered from band traps and only three adult males emerged. The unsuccessful development of codling moth is attributed mainly to the poor host quality of cherries for this species. Cannibalism, though not observed, was suspected as another mortality factor. Using a minimum estimated initial egg count of 4225 eggs (the total number of eggs laid on the apple fruits), generation survival was less than 0.1%.

2.3. Biology, life history, and phenology

Codling moth overwinters as diapausing fifth instar larvae in cocoons under the bark and in cracks and crevices of its host trees. Some may overwinter on the ground and in trash beneath the trees, and a small percentage may stay in diapause through two winters (Yothers and Carlson, 1941; Garlick, 1948). Larval diapause ends due to chilling, a long photoperiod, or both (Riedl, 1983). The larvae pupate in the spring and adult emergence may extend over the summer (e.g. South Island, New Zealand) or occur earlier and be more synchronised, leading to further generations over the summer (e.g. Washington State, USA).

The sex ratio of adults is approximately 1 : 1. Sexual reproduction is obligatory and both sexes may mate

more than once. Codling moth adults are capable of mating 12 h after emergence (Gehring and Madsen, 1963), and most female sexual activity occurs within four days of eclosion (Howell et al., 1978). Adult males are attracted over long distances to adult females by way of a sex pheromone (McDonough et al., 1969). The female has her full complement of eggs at eclosion, and they are matured and laid individually. Females start ovipositing the day after mating (Gehring and Madsen, 1963). Egg production per female varies among individuals, locations, and seasons, ranging from 0 to 284, but it often averages 50–100 eggs laid per female (Geier, 1963; Wearing and Ferguson, 1971). Wearing and Ferguson (1971) observed that variation in fecundity is prominent in areas where yearly weather conditions fluctuate. Later season broods are more fecund than spring broods (Putman, 1963).

Eggs are laid singly on leaves, fruits, and twigs of the host tree, with > 90% within 10 cm of the fruit on apple trees (Wearing et al., 1973; Jackson, 1979). Hagley et al. (1980) found an inverse relationship between oviposition and pubescence of plant surfaces. Egg laying is stimulated by the odour of apple fruits, including alpha-farnesene (Wearing and Hutchins, 1973), which also acts as an attractant to first instar larvae hatching from the eggs (Sutherland et al., 1974). The first instar larva often enters apples through the calyx, and prefers entry on the ripe side of the fruit. After entering on the open surface, the larva constructs a spiral gallery just beneath the apple "skin", before moulting and beginning radial penetration to the centre. Rate of development increases when larvae feed on seeds, whereas larvae destined to diapause feed longer than non-diapausing larvae (Putman, 1963). Larvae have been reared on apple leaves with limited success (Hall, 1934), but those that reached maturity did not produce eggs (Heriot and Waddell, 1942). Five larval instars are completed in the fruit, although some larvae move between fruits, and the fully developed caterpillar then leaves to seek a cocooning site. At this stage, the larva may be in non-diapause or diapause condition, depending on the temperatures and daylength which it has experienced (i.e. time of year and location (latitude)).

The population dynamics and mortality of codling moth on apple have been investigated in many countries, including in the USA by Brown et al. (1978) and Ferro et al. (1974) and in New Zealand by Wearing (1979). Codling moth is so extremely rare in cherries that most of the density-related mortality factors (e.g., predation, parasitism, intraspecific competition) would have little impact on codling moth survival on cherry trees. However, the carrying capacity of the fruit may determine larval survival. When fruits are small, such as immature apples, there may be food for only one larva (Ferro and Harwood, 1973), and food may be limiting in individual cherries, particularly early in the season.

The phenology of codling moth is largely determined by temperature, and this is critical in determining the stages which conceivably could be present on or in cherries at the time of harvest and export. The rate of development is dependent on accumulated degree-days above a base threshold of development which for codling moth is 10 or 11°C in different models (e.g., Bethell, 1978; Welch et al., 1978; Beers et al., 1993). Pitcairn et al. (1991), while studying larval development at constant temperatures, found no survivors below 12.2°C or above 34.4°C. Heat units for phenology models often are accumulated from a "biofix" in spring, which may be the first catch of a codling moth male in a pheromone trap (e.g., Riedl et al., 1976; Pitcairn et al., 1992). Egg hatch and adult emergence of codling moth in Washington State has been successfully predicted with this approach (Brunner et al., 1982; Beers and Brunner, 1992), and Blago (1992) was able to adapt the California phenology model to conditions in Germany by using only the daily minimum and maximum air temperatures.

2.3.1. Codling moth life cycle and phenology in USA in relation to cherry

Codling moth phenology is variable in western USA. In the Pacific Northwest, two generations are the norm, with a third occurring in warm years (Beers et al., 1993) (Fig. 1). In California, there may be up to four generations per year (Ohlendorf, 1991). Furthermore, the topography of these regions is so varied that growing areas may be in distinct climatic zones even though separated by short distances. Therefore, it is necessary to measure temperatures at specific locations to determine development of both cherries and codling moth. Phenology models (see previous section) are accurate in predicting adult emergence in the spring. The first moth flight is usually distinct, but later flights become more difficult to separate because of overlapping generations from locations with different temperature accumulations.

In areas where codling moth is bi- or multi-voltine, the life cycle has two types of diapause, a vernal diapause, involving a small proportion of the first generation, and an autumn diapause, which enables the insect to overwinter (Ohlendorf, 1991). Riedl (1983) reviewed the factors involved in both types of diapause. Riedl and Croft (1978) predicted vernal diapause based on heat units but Brown et al. (1978) attributed vernal diapause to an adaptive response to density by larvae with insufficient nutrition. Winter diapause is associated with the reduction of photoperiod during late summer (Riedl, 1983). Factors that may modify photoperiod reaction to diapause response are low summer temperatures and nutritional relationship due to host maturity (Riedl, 1983).

Cherry cultivars have been developed with specific fruiting patterns so that producers now can predict harvest time and when to initiate pest control. For example, in the Pacific Northwest, "Chelan" cherries can be picked as early as late May while "Sweethearts" are harvested in
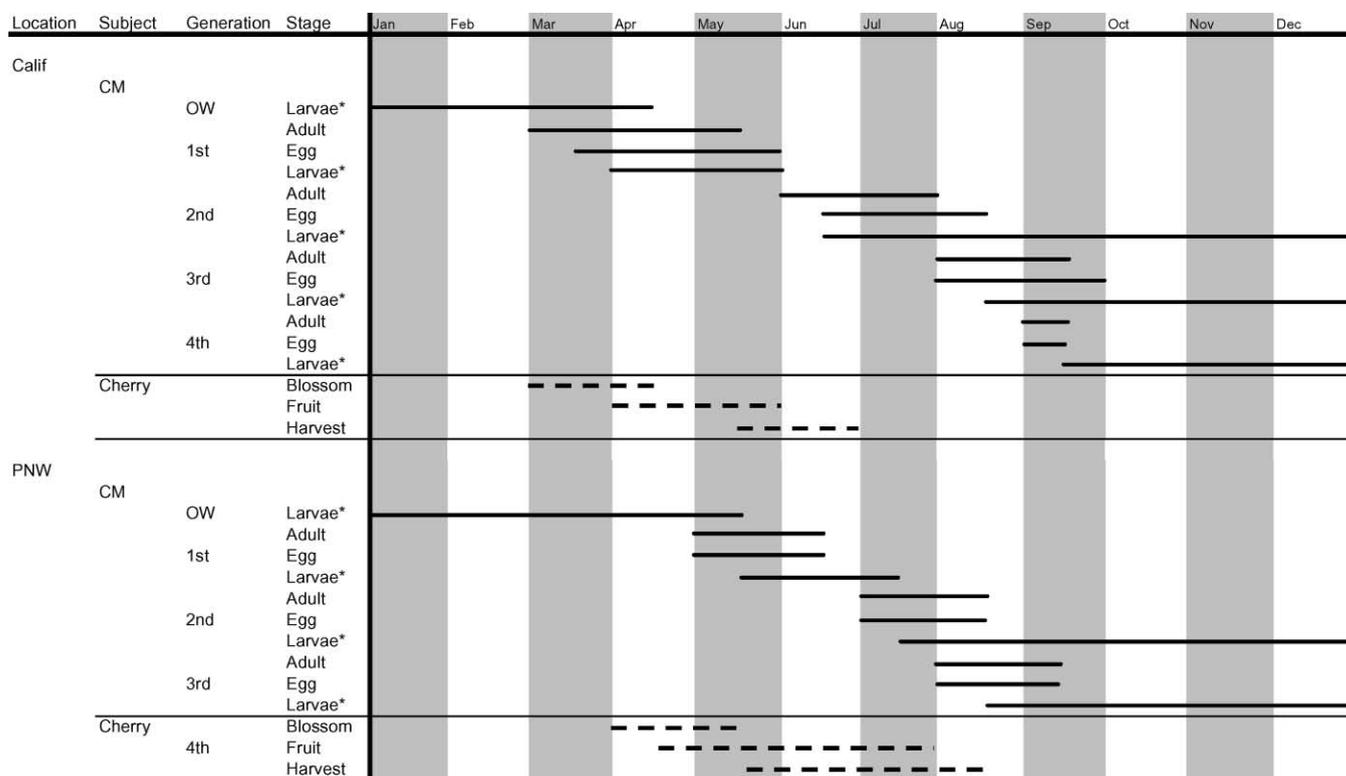
Fig. 1. Life cycle of codling moth and cherry phenology in California and Pacific Northwest, USA.

* Includes pupae.

August. Generally, moths from the overwinter brood emerge at time of full bloom of "Delicious" apples and their next generation would start to pupate in late June, several weeks after all "Chelan" and early "Bings" have been harvested. Cherries differ from apples in that they are harvested much earlier, making it difficult for the second generation of codling moth to attack the crop.

With the range of harvest dates of different cherry cultivars now available, the stages of codling moth that theoretically could be present on export cherries at harvest in western USA are eggs and all larval instars (Fig. 1). Because diapausing larvae, pupae, and adults are not found in cherry and apple fruits, these stages are not of any quarantine concern for those commodities.

2.3.2. Codling moth life cycle and phenology in New Zealand in relation to cherry

The sweet cherry exporting areas of New Zealand are Central Otago and Marlborough in the South Island, where codling moth completes one full generation per year and a small partial second generation in warm seasons (Wearing, 1974). The proportion of the population which enters the second generation does not exceed 2% and is only a part of those early larvae which com-

plete development by about the first week of January each season. The life cycle is summarised in Fig. 2.

As in other parts of the world, the timing of the life cycle is earlier or later depending on ambient temperatures in a given season (e.g., Pitcairn et al., 1992). Adults emerge from October to February and the earliest time that egg laying occurs is in early November. Cherry harvesting and exporting is carried out from the beginning of December to late January, giving the theoretical potential for codling moth infestation of the sweet cherry fruits by eggs and various larval instars, depending on the harvest date of specific cherry varieties in different regions. Trials were carried out from 1979–1982 (Wearing et al., 1980, 1983), in which codling moth adults were caged (forced to develop) on cherries. This study showed that on cv. "Dawson", codling moth larvae reached a maximum of third and fourth instar, respectively, at harvest in Marlborough and Central Otago; on cv. "Bing", the larvae reached, respectively, a maximum of fourth and fifth instar by harvest time. Under natural conditions, most of the codling moth population at these cherry harvest times are either pupae and adults from the overwintered population, and eggs and young larvae from the new summer generation. Very few larvae have developed to the fully fed fifth instar. As expected, almost all the larvae subsequently entered diapause after leaving the cherries. (Wearing et al., 1980, 1983).

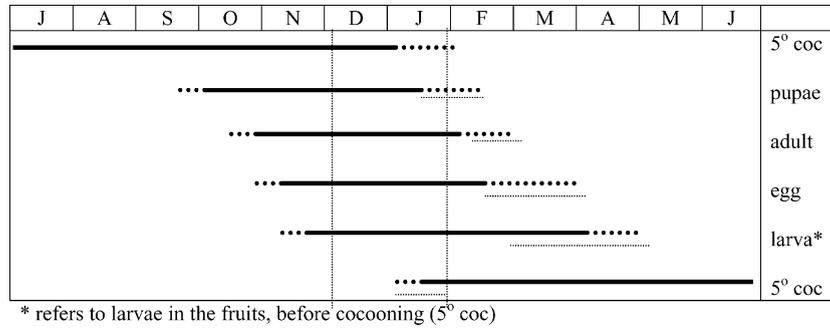* refers to larvae in the fruits, before cocooning (5° coc)

Fig. 2. Life cycle of codling moth on apple in the South Island of New Zealand. Solid lines refer to the occurrence in most seasons and the dotted extensions to variations in some years. (······) refers to the partial second generation when it occurs. Vertical dotted lines identify the cherry exporting period.

2.4. Incidence of codling moth in cherry groves and harvested cherries in USA and New Zealand

2.4.1. USA

Cherries from western USA must be inspected and certified to be free of codling moth before being exported. From 1978 to 1999, over 18 million cartons of cherries were certified for export to Japan and Korea, with inspectors finding only 12 suspected codling moth larvae, all but one from California (Moffitt, 1997, Table 2).

Recent records from USDA-APHIS and Northwest Fruit Exporters (Yakima, Washington) show that 4 million cartons of sweet cherries were certified and exported between 1997 and 1999 from the West Coast states of the USA. In the inspections, only four suspect codling moth larvae were found in 1997, all from California cherries. Over the 21 yr of exporting (Table 2), the total of 12 suspected codling moth larvae were found in an estimated 777.4 million cherries giving an infestation rate of 1.54×10^{-8}.

In early 1999, a study was conducted in the Yakima Valley, Washington, to determine if codling moths could be found in commercial cherry orchards. Pheromone traps used to sample adult males were placed in twelve cherry orchards and twelve apple and pear orchards (control orchards), each adjoining a surveyed cherry orchard. Adult moths were collected from all control orchards with an early season average of 104.3 ± 22.8 moths per orchard. Moths were found in only seven cherry orchards with an average of 9.5 ± 3.5 moths per orchard. In cherry orchards where male moths were found, molasses traps were set up to collect female adult moths and band traps were applied to tree trunks to capture pupating larvae. However, no codling moths were caught in either the molasses or band traps (Hansen et al., 1999). These results are consistent with those from New Zealand (Wearing and McLaren, 2001) indicating that, while codling moth adults were present in the cherry orchards, no evidence of crop infestation was found.

Sweet cherries in the Pacific Northwest (including those in the above trials) are exposed to an assortment of insecticides to control a variety of pests, particularly western cherry fruit fly, *Rhagoletis indifferens* Curran (Diptera: Tephritidae), which is a regulated pest for out-of-state shipments. Although codling moth is not targeted, some of the chemicals applied against these other pests are the same as those used for codling moth control. Furthermore, cherry orchards are often intermingled with pear and apple orchards, and their spray programmes against codling moth would benefit neighbouring cherry orchards. Hence, the likelihood of finding codling moth infesting cherries in a cherry orchard, surrounded by a well-managed apple orchard, would be remote, regardless of the host status of cherries.

2.4.2. New Zealand

The New Zealand Ministry of Agriculture and Forestry (MAF) maintains a national list of pests occurring on different crops, including cherries. The primary source of data for the cherry list is the PPIN database (Plant Pest Information Network (PPIN) database, Ministry of Agriculture and Forestry, New Zealand) which includes published records, MAF diagnostic laboratory records and records from other research organisations, and the pest information from a recent stonefruit national survey (Anonymous, 1998). There is no record of codling moth attacking sweet cherry in New Zealand (MAF Biosecurity Authority cherry fruit pest list, October 1999), and this has been demonstrated to be the situation even in blocks of cherries adjacent or near to abandoned apple blocks heavily infested with codling moth (Wearing and McLaren, 2001). These extensive data collection procedures provide strong evidence that codling moth does not occur on sweet cherry in New Zealand.

Another factor contributing to the absence of codling moth in cherries is the excellent control of codling moth in commercial pome fruit orchards in New Zealand using organophosphates, carbamates, and more recently, insect growth regulators. The combined need to control leafrollers and codling moth, as well as other insects, means that the incidence of codling moth in harvested commercial apples is extremely rare (Wearing, 1995). Organophosphates are also used to protect export cherries from leafroller damage, thereby reducing even further the

risk of codling moth in commercial cherries. Even unsprayed cherries adjacent to abandoned apples were not damaged by codling moth (Wearing and McLaren, 2001), indicating that the normal commercial risk in sprayed orchards is negligible.

The volume of exports of cherries from New Zealand is considerably less than from the USA. New Zealand cherries are shipped to a variety of markets, and samples are routinely inspected either by MAF staff or by trained quality control officers employed by the packhouses. In addition, a proportion of cherries are fumigated and shipped to Japan (Table 3, Summerfruit New Zealand Inc., 1999) following joint inspection of 2% of the exports by Japanese and New Zealand quarantine personnel. A summary of inspection data is provided in Table 3 (average weight per cherry = 7.4 g, McLaren and King, unpublished) and no codling moth have ever been sighted during these procedures.

Further investigations traced the inspection records of packhouse quality control officers back to 1993–94 and found that no codling moths have been sighted on a total of 1,024,352 sweet cherries. When the New Zealand data are compared with the much larger data set of USA inspections, it is clear that codling moth is so rare in sweet cherries in USA that it is unlikely ever to be found during inspections of New Zealand cherries. Moreover, codling moth has never been recorded on sweet cherry in New Zealand. It is our contention that the best available estimate for the probability of codling moth occurring in New Zealand cherries is either zero or that based on the USA data in which the largest numbers of cherries have been inspected (Table 2).

2.5. Survival in cherry during storage and transit

Codling moths in transit to Japan may experience some mortality due to shipment conditions. The current shipment method for New Zealand cherries is by airfreight, with the cherries remaining in cool storage (0.5°C) on the one to two-day journey. Codling moth eggs on wax-paper sheets, subjected to half a day in standard cool storage conditions, experienced mortalities of 33, 20 and 27% for 1-, 3- and 5-day old eggs, respectively (Batchelor et al., 1987). After a day in cool storage, mortalities were 34, 24, and 31%. Control mortalities for these eggs (at 25°C) were 24, 14 and 13%, respectively. However, Bollen et al. (1998) found that asparagus air freighted from New Zealand to Japan in cool storage does not remain at a constant temperature, and may reach temperatures of 23°C upon arrival in Singapore before being loaded aboard the flight to Tokyo. Thus, significant mortality due to cool storage during air shipment from New Zealand may not occur.

Batchelor et al. (1987) presented data on mortality experienced by eggs and fifth-instar codling moth larvae in apples held under either controlled-atmosphere (CA) or cool storage conditions for longer periods of time. The data suggest that if cherries were shipped by sea (approximately a 14-day journey) to Japan in either cool storage or CA, significant egg and larval mortality could result.

Fruit from the USA may be shipped by air or sea and conditions are not standardized. Only a low level of mortality of eggs and larvae would be expected from cool storage during the brief journey of 10 h by air. Greater mortality may be expected in the period of 10 d of seafreight but this has not been studied directly. In the laboratory, the effect of cold storage (3.3°C) was studied on the survival of first instar larvae in cherries (Hansen, unpublished). This is in the temperature range one would expect for cherries in transit from the USA and held at wholesale and retail facilities. However, no significant differences in mortality were observed between the control and treated larvae until ⩾a week of cold. The longest period of storage (two weeks) had the highest mortality of first instars (ave ± se = 27.5 ± 2.5%) among traditionally grown sweet cherries (Hansen, 1999b).

In recent laboratory research, codling moth larvae were examined to determine if they would move from infested fruits to uninfested fruits, such as in transit, when cherries are packed in a common container (Hansen, unpublished). Cherries are typically transported under refrigeration, but this experiment was conducted at room temperatures (25°C) so that cold temperatures would not

Table 3
Cherry exports from New Zealand and the numbers of cherries inspected

Year	Cherries exported (kg)	No. of cherries inspected (for markets other than Japan) (NZMAF)[a]	Cherries exported to Japan (kg)	No. of cherries inspected (2%) for Japan
1987/88	58,000	250	15,573	42,089
1988/89	122,000	—	56,171	151,814
1989/90	198,000	3729	50,367	136,127
1990/91	367,000	22,513	47,514	128,416
1991/92	492,000	28,681	61,104	165,146
1992/93	433,000	27,867	43,682	118,059
1993/94	227,873	27,000	33,435	90,365
1994/95	603,771	31,000	31,579	85,349
1995/96	218,078	25,200	24,797	67,019
1996/97	348,835	—	29,041	78,489
1997/98	643,346	30,600	25,094	67,822
1998/99	454,000	54,000	11,244	30,389
Total	4,165,903	250,840	429,601	1,161,084

[a] These data refer to those inspections which could be traced and does not cover all inspections which were carried out; — data not available.

impede the insects. No movement was observed in 72.5% first instars, 100% of second and third instars, and 87.5% of fourth and fifth instars. All cherries became mouldy within a week.

3. Factors affecting the risk of establishment of codling moth in cherry after arrival in Japan

3.1. Survival and development

Sweet cherries are a perishable commodity and require continual refrigeration to maintain quality. As indicated earlier, codling moths need accumulated heat units to develop, and larvae do not move under cold conditions. If cherries are held in cold storage until time of consumption, there is no opportunity for larval development, dispersal to pupation sites, and adult emergence.

For codling moths to become established, infested fruits must be recognized, not consumed, and disposed of under circumstances where larvae survive and develop. There are very few scenarios where this could happen, but the most consequential would be where the infested cherry would commingle with other fruits so that the larva could find a suitable food source, continue development, emerge as an adult, find a partner, mate, and oviposit on other fruits. However, our laboratory data (Hansen, unpublished) indicate that larvae remain in cherry fruits, most of the time, after harvest. This observation is also supported by field data from the caged tree experiment (see earlier specific studies). Furthermore, considering the rarity of a successful development, it would have to occur at least twice, at the same time, and with individuals of different sexes. Each event is overlaid with a low probability, and yet these must occur in sequence under ideal circumstances.

Laboratory and field research have indicated that only a small percentage (1–16% on different cultivars and < 0.1%, respectively) of codling moth larvae, forced to live on sweet cherry alone, survive to produce adult moths (Hansen, unpublished; Hansen, 1999a; Hansen and Rehmke, in prep.). The infested cherries rot quickly at ambient temperature. There is, therefore, a very low probability of survival for a codling moth larva in an infested cherry discarded in a site which provides no other food source.

3.2. Dispersal

In the unlikely event that a codling moth larva from an imported sweet cherry survives to reach adult in a country such as Japan, the adult moth will not be able to establish a population unless (1) it mates with a conspecific, and (2) the female is able to disperse to a suitable host plant at a suitable stage of development. The latter may occur while the female is still a virgin, such that the female then releases pheromone to attract a male for mating, or it may occur after the female has mated at the site of its emergence. In all the various circumstances that may surround a moth at the time of moth emergence (e.g., in a rubbish dump, compost heap), the dispersal ability of both the male and female moths will play an important role in determining whether population establishment occurs.

The mobility of codling moth in the field has been studied in many locations (e.g., Howell and Clift, 1974; White and Hutt, 1975; Mani and Wildbolz, 1977; Causse, 1978). Males vary greatly in their mobility. Mani and Wildbolz (1977) reported that about 80% of males were recaptured up to 1 km from their point of release; similarly, Vojnits (1972) recorded most males moving several hundred metres. However, there are highly mobile moths in the population which move up to 4.8 km (Butt and Steiner, 1969) or even up to 11 km (Mani and Wildbolz, 1977). Howell and Clift (1974) conducted a detailed study of the dispersal of released moths both within and outside apple orchards. Moths were recaptured with both blacklight traps and traps baited with virgin females. Males released in the centres of two orchards (31 and 137 ha) dispersed throughout the plantings within one week, with movement respectively up to 425 and 900 m (i.e., to the boundaries). Of the released moths, 1.2% reached the most distant traps. Dispersal was reduced by the concurrent release of females; in their presence only 1.5% of males were captured beyond 300 m. Mani and Wildbolz (1978) found that male moths released within a 5 ha orchard moved beyond the orchard boundary and up to 200 m into woodland. When moths were released by Howell and Clift (1974) outside orchards, they dispersed much greater distances (up to 8.4 km) over varied terrain and into orchards and abandoned fruit trees.

Some studies of mated females have suggested that they are considerably less mobile (50–150 m dispersal) than males (e.g., Wildbolz and Baggiolini, 1959; Howell and Clift, 1974), or that females may even be relatively sedentary (Geier, 1963). This has resulted in proposals that 100 m could be an effective barrier to immigration of mated females from infested trees, either into commercial orchards (Kneifl, 1988) or into mating disruption trials (Charmillot, 1990). However, this barrier was not found adequate in New Zealand trials (Wearing, unpublished), and this is confirmed by the work of White et al. (1972). They reported that mated females dispersed up to 600 m with 90% recaptured within 300 m. This is still considerably less than the dispersal distance of males and continues to suggest that female codling moths are less mobile. However, this must be treated with caution because there is no trapping method for recapturing marked females which is as efficient as pheromone traps for males. The movement of virgin female moths has not been reported in the field.

Recent detailed flight mill studies (Schumacher et al., 1997a) provide strong evidence that female codling moths (virgin and mated) are indeed as mobile as the males. This research has confirmed the wide variation in flight capacity of individual moths, as reported from the field, but showed that 13.3% of males and 13.7% of females undertook long single flights (>5 km or about 120 min). These summary data refer to a mixed population of mated and virgin moths of each sex ranging in age from 0–14 d. About 16.7% of virgin and 10% of mated males, and 20% of virgin and 7.4% of mated females undertook these long flights. Flight mill studies do not provide a direct measure of the distance of displacement by moths in the field (e.g., moths do not fly in a single direction in the field), but they do show the high mobility of a proportion of adult moths. Schumacher et al. (1997a) concluded that both males and females can undertake single flights of up to 11 km, as reported for males in the field. Moreover, the total flight distance of males and females could be greater than this. For example, a virgin female moth on the flight mill flew four times to reach a maximum of 37 km. The ability of a proportion of the codling moth population to fly long distances would provide a means of inter-habitat movement, enabling colonization of widely dispersed apple trees in natural forests in the area of origin of the species. This contrasts with the situation in apple orchards today in which short distance flights would normally enable a codling moth to reach another host plant.

It is highly improbable that a codling moth emerging from a cherry after arrival in Japan would do so within an apple orchard. The circumstances for a moth emerging in a fruit dump site may require flight of considerable distance to locate a mate and/or a host plant. The flight mill studies (Schumacher et al., 1997a) showed that there is a continuous distribution of flight capacity among the codling moth population with about 15% undertaking long single flights of 5 km or more, and 5% exceeding 10 km. A scenario for codling moth establishment would appear to require a male and female moth emerging within 10–15 km of one another and a host plant within similar range of the female moth. The proportion of moths able to achieve mating and host location would increase substantially as the distances between the two moths, and between the female and the host plant, reduces from 15 to 0 km. In addition, the male would need to be located downwind from a calling female (i.e., within the pheromone plume) and within this dispersal range.

Schumacher et al. (1997a) also showed that flight activity was negatively correlated with the fecundity and longevity of female moths. As the distance flown to a host plant increases, a reduction in the fecundity of the female on arrival can be expected. This would reduce the probability of codling moth establishment. Further research by Schumacher et al. (1997b) with a field-collected strain

of codling moth has shown high genetic correlations between the total distances flown by the moths and their body weights and wing lengths. The reduced size of codling moth which have developed on cherries (see earlier specific studies) compared to apples would be expected to reduce the flight capacity of the adult moths, and further reduce the risk of both mate and host plant location in a new locality.

4. Modelling risk assessment

4.1. General description of the model

The probability of codling moth infesting cherries and subsequently infesting hosts in Japan was estimated using a model similar to those of Whyte et al. (1996), Vail et al. (1993), and Baker et al. (1990). Components of the model include:

- export volumes and infestation levels determined by inspection to estimate the number of infested cherries exported per consignment in a year;
- biological data to estimate the proportion of individuals in the infested fruit likely to survive in transit and storage;
- climate, population, and host distribution data in the destination country (Japan) to predict the proportion of infested fruit that could arrive in an area suitable for codling moth establishment, and
- biological data to estimate the proportion of individuals in the infested fruit likely to survive and reproduce in Japan.

The model uses the following rationale:

If p is the probability of an export cherry being infested with codling moth (equivalent to the infestation level) and N is the number of cherries in a particular consignment, then Np is the number of codling moth-infested cherries exported in that consignment. Only one codling moth larva per cherry completed development when moths were forced to lay on cherries for disinfestation research (Wearing et al., 1983), so that Np is also the number of immature moths in the consignment.

Wearing et al. (1983) showed that at harvest, New Zealand cherries of certain cultivars could potentially carry eggs and larval instars 1–5 at the time of picking. The same stages could potentially occur in USA cherries over the range of harvest dates from May to August. Different instars of codling moth will have different probabilities of survival, so a subscript is used to denote different immature stages. The number of immature moths shipped in a consignment will therefore be $N \sum p_i$, where p_i is the proportion of cherries infested with a particular immature stage of codling moth. Conditions of transit and storage may cause varying degrees of mortality for eggs on the outside of fruit and larvae inside. If

φ_i is the proportion of a particular larval stage surviving transit, then the number of live immature moths arriving in Japan in the consignment will be $N\sum p_i\varphi_i$.

Upon arrival in Japan, some of the infested cherries may be disposed of in retail outlets during repackaging for sale. Larval damage to cherries becomes increasingly obvious as the larvae grow, and culling of fruit infested by any late instar codling moth larvae is particularly likely. In order for an establishment to occur, the larvae in the cherries must be disposed of in an area suitable for continued development to the adult stage. This could include parks, gardens, roadsides or other vegetated areas. Continued development would also depend on suitable food and temperatures, and establishment would require host trees within flight range (see the section on Dispersal) of the disposal site. Infested cherries rot quickly (see earlier sections) and more than one cherry, or other food, is likely needed for the survival of young larvae. The probability of these environmental factors (disposal outside, suitable climate, and hosts available) being suitable for continued development and establishment can be considered as a single factor, Ψ_t. Thus, the expected number of codling moths from the consignment arriving in an area suitable for establishment can be written as $N\sum p_i\varphi_i\Psi_i$.

Not all individuals making it to such an area will necessarily survive to adulthood (see the section on Survival and development). Some may die from starvation related to the deteriorating cherry, while others succumb to natural enemies. For example, larvae emerging from cherries could be eaten by birds (Audemard, 1991), spiders (Wearing and Skilling, 1975), or other organisms. If ϕ_i is the proportion of individuals of a particular stage that survive to adulthood, then $N\sum p_i\varphi_i\Psi_i\phi_i$ is the expected number of adult codling moths from the consignment available to start a new population.

A male and female must then meet and mate before infestation can occur. With equal sex ratios, the probability of at least one male and one female being present in x individuals is $1-0.5^{x-1}$ (Landolt et al., 1984). This is then multiplied by the probability of a given number of individuals surviving, based on the expected number ($N\sum p_i\varphi_i\Psi_i\phi_i$) and summed for $x>1$. Baker et al. (1990) give a simplified version of the sum, where the probability of a male and female from an expected number of individuals, λ, equals $1+\exp(-\lambda)-2\exp(-\lambda/2)$. Substituting $N\sum p_i\varphi_i\Psi_i\phi_i$ for λ gives the probability of at least one male and one female moth surviving from a consignment of cherries. If there are m consignments in a season, $1-(1-[1+\exp(-\lambda)-2\exp(-\lambda/2)])^m$ gives the likelihood that a male and female moth will survive from at least one of the m consignments. This probability should be extremely small to give a high level of protection against codling moth introduction to Japan.

4.2. Discussion of the model components

4.2.1. Number of cherries exported per year

Sweet cherry exports from the Pacific Northwest of USA to Japan and Korea totalled 19,872 tonnes in the period 1978 to 1986 (Table 2), or an average of 2208 tonnes per year. This increased to an average of 5853 tonnes per year from 1987 to 1996 and, in the same period, Californian exports averaged 4561 tonnes per year. Over the last three years, exports from the Pacific Northwest averaged 5274 tonnes and from California, 7157 tonnes. These tonnages are estimated respectively to contain 732.5 million cherries and 1420.0 million cherries (see Table 2), giving a total of 2.15 billion cherries per year.

California cherries are shipped mainly from mid-May to mid-June, and Pacific Northwest cherries from mid-June to late July. Between 60 and 90% of the total cherries shipped on any given day go to Narita airport or Tokyo port (data provided by J. Christie, California Cherry Advisory Board and J. Archer, Northwest Fruit Exporters). Baker et al. (1990) considered that the total amount of host material arriving in a particular place within a given time period should be used in estimating the risk of exotic pest establishment. Because commercial produce is distributed soon after arrival, Baker et al. (1990) assessed the likelihood of immature insects arriving on different days and being distributed to the same place as negligible, and so used the amount of host material arriving on a single day in one place to calculate the maximum pest limit. The median daily cherry shipment to Narita/Tokyo in 1999 was 20.5 million cherries: this is used to estimate the per-shipment risk of codling moth establishment, and the seasonal risk is calculated based on approximately 100 shipments of this size (2.15 billion cherries/20.5 million per shipment).

In the last 12 yr, New Zealand has exported 429.6 tonnes of cherries to Japan, an average of 35.8 tonnes per year (see Table 3, (Summerfruit New Zealand Inc., 1999)). However, recent export volumes have been lower, averaging 24.35 tonnes per year in the last 5 yr. Experimental work, in which export cherries were weighed (McLaren and King, unpublished), have shown that New Zealand cherries average 7.4 g (range 6.5–8.4 g for samples of 500 cherries). An average of 24.35 tonnes equates to 3,290,541 cherries exported per year. However, should market access criteria change for New Zealand cherries entering Japan, this number could increase by up to 10 times. The New Zealand model calculates the probability of establishment from 33 million cherries shipped annually, in 28 daily consignments (1 every 2 d during the cherry season).

4.2.2. Infestation of cherries by codling moth

4.2.2.1. Proportion of cherries infested. Inspections of New Zealand cherries prior to export to Japan by NZ

MAF and the Japanese MAFF (Ministry of Agriculture, Fisheries and Forestry) have never found codling moth. Over the last 12 yr, the 2% samples of export cherries inspected total 1,161,084 (see Table 3). Using the method of Couey and Chew (1986), the upper 95% confidence limit for the proportion of cherries infested, based on the combined data, is 2.6×10^{-6}. However, this estimate is dependent entirely on the number of cherries inspected because no infested cherries have been found. It is not, therefore, an accurate reflection of the level of codling moth infestation in cherries (see earlier description of codling moth incidence in New Zealand cherries).

The only records of codling moth infesting cherries come from the USA. United States Department of Agriculture (USDA) inspection records (Table 2) show 7 cherries infested with codling moth from 221 million Californian cherries inspected from 1987 to 1996 and 1 infested cherry from a total of 491.8 million cherries inspected in the Pacific Northwest from 1978–96. Records from 1997–99 show 4 possible interceptions of codling moth in 42.6 million cherries from Californian inspections but no interceptions in Pacific Northwest cherries (22.0 million). The estimated proportion of cherries infested with codling moth would be 1.54×10^{-8} (1978–99 data), with upper 95% and 99% confidence limits of 2.50×10^{-8} and 2.94×10^{-8}.

The above assumes that the efficacy of inspection is 100%, or that all infested cherries examined would be correctly identified as infested. For later infestations, efficacy is likely to be close to 100%, as late instar larvae cause severe fruit damage. However, egg or early instar infestations could be missed. Gould (1995) found that the efficacy of fruit cutting for detecting fruit fly infestation varied from 18 to 84%, suggesting that visual inspection for this pest would have had an even lower efficacy.

For Japan MAFF inspections of New Zealand export cherries, inspectors can rely on external symptoms of codling moth, and they use hand lenses to minutely examine fruit. We estimate that the efficacy of detection would be significantly greater than that reported for fruit fly, and would be at least 60% for eggs, 70% for first instar larvae, 80% for second instar, 90% for third instar, 95% for fourth instar and 99% for fifth instar larvae.

4.2.2.2. Stage of development at cherry harvest. Light trap catches of female codling moths provide a good indication of the timing of their emergence (Wearing and Walker, 1998). Data from Nelson, New Zealand (at the same latitude as Marlborough) over several seasons in the late 1950s show that females begin to emerge in mid-to-late November, depending on seasonal temperature fluctuations (Wearing and Walker, 1998). The data were combined to give a distribution of female emergence over the season, using the first day females appeared in traps as day 1. Female codling moths lay their eggs over an average of approximately two weeks (Wearing and

Walker, 1998; Wearing, 1979) and, for the model, this was assumed to be distributed evenly over this period beginning with the date of emergence. Thus, if 5% of the season's females were caught in a given week, it was assumed that 2.5% of the season's eggs would be laid that week, and 2.5% the following week. This gave a distribution for the eggs laid in a season as shown in Fig. 3.

A degree-day model was then applied to Otago and Marlborough temperature data, to predict the stage that eggs laid in a given week in each region would reach by harvest, as follows.

Egg development may require 87.8 degree-days above $10°$ (UC SIPMP) or 88.9 degree-days above $11.1°C$ (Bethell, 1978). Larval development in apples and pears may take 261.7 degree-days above $10°C$ (UC SIPMP) or 263.9 degree-days above $11.1°C$ (Bethell, 1978). However, larval development in cherry may take longer than in preferred hosts. Wearing et al. (1983) found that after 452 degree-days above $10°C$, 15% of codling moth larvae in "Bing" cherries were in fourth instar and 85% in fifth instar. Hansen et al. (1999) found that newly hatched larvae of codling moth, when placed in "Bing" cherries and kept at $25°C$, required 32 d (organic cherries) and 36.6 d (conventional cherries) to complete fifth instar development. These figures are equivalent to 480 and 549 degree-days above $10°C$, respectively.

The larval instars develop at different rates. Setyobudi (1989) gave degree-day requirements for development of codling moth larvae of 289 above a threshold temperature of $11.2°C$ (males and females combined). Of this, 19% of the time was spent in each of the first and second instars, 11% in the third instar, 7% in the fourth instar, and 43% in the fifth instar (CMISS, 1999). The figures of Hansen et al. (1999) suggest that the first instar requires 14% of the total larval developmental time, the second instar 13–18%, the third instar 24–36%, the fourth instar 12–15%, and the fifth instar 24–29%.

For the model, 88 degree-days above $10°C$ were assumed to be required for egg development, and 350 degree-days for larval development (midway between the field values for codling moths in other hosts and laboratory values in cherries). The percentage of larval development time spent in each instar was assumed to be as found by Setyobudi (1989). Based on these data, and assuming that the first females emerge on 1 November, with eggs added to the population as shown in Fig. 3, the model predicts that the distribution of the immature codling moth population at various harvest dates would be approximately as shown in Table 4. Temperature data from 1997–98 were used to calculate accumulated degree-days for Blenheim and Alexandra for the dates in Table 4.

Codling moths caged on cherry trees in Marlborough, New Zealand in the 1979–80 season laid 80% of their eggs on the foliage (Wearing, unpublished) and in Washington State at least 66% (Hansen et al., 1999). Assuming
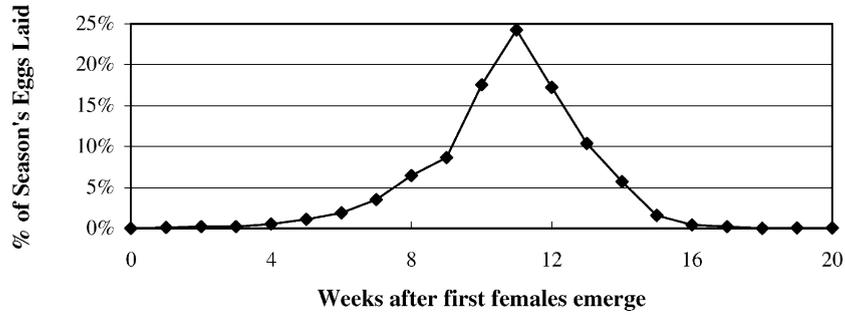
Fig. 3. Predicted addition of codling moth eggs to population.

Table 4
Predicted population distribution of immature codling moths in the South Island, New Zealand

Harvest date	Blenheim						Alexandra					
% of pop. in stage	Egg	1st	2nd	3rd	4th	5th	Egg	1st	2nd	3rd	4th	5th
6 December	52	43	5	0	0	0	100	0	0	0	0	0
13 December	48	40	9	3	0	0	88	12	0	0	0	0
20 December	47	25	15	9	2	1	94	6	0	0	0	0
27 December	46	25	14	8	5	2	85	13	2	0	0	0
3 January	38	28	16	8	5	4	82	13	4	0	0	0
10 January	44	38	9	0	5	5	44	46	9	1	0	0
17 January	38	41	10	0	5	6	38	27	29	5	1	1
24 January	21	52	11	8	0	8	21	30	32	12	2	3
31 January	31	27	20	10	7	6	11	19	45	0	9	15

Table 5
Predicted distribution of codling moths in cherry fruits at harvest, South Island, New Zealand

Harvest date	Blenheim						Alexandra					
% of population at	Egg	1st	2nd	3rd	4th	5th	Egg	1st	2nd	3rd	4th	5th
6 December	18	73	9	0	0	0	100	0	0	0	0	0
13 December	15	65	15	4	0	0	59	41	0	0	0	0
20 December	15	40	23	15	4	2	75	25	0	0	0	0
27 December	15	40	22	12	8	3	53	40	7	0	0	0
3 January	11	41	22	12	7	6	49	39	13	0	0	0
10 January	14	58	13	0	7	8	14	71	13	1	0	0
17 January	11	59	14	0	8	8	11	39	41	7	1	1
24 January	5	63	13	10	0	10	5	36	39	15	3	3
31 January	8	36	26	13	9	8	2	21	50	0	10	17

that no more than 20% of eggs are laid on fruit, the proportion of the population in fruit in a particular stage of development at a given date would be found by taking the figure from Table 4 and dividing by 0.2 times the proportion in egg stage plus the proportion in all larval instars. The predicted proportion of codling moth in fruit in each immature stage is shown in Table 5.

It should be noted that in the model, the eggs added to the population each week were assumed to be in the same developmental stage at a given date, so that occasionally, no individuals were predicted to be in a particular instar.

4.2.2.3. Number of infested cherries exported. It is assumed in the model that New Zealand cherry exports could increase ten-fold if fumigation was not required. Using a value of 33 million for N and 1.54×10^{-8} for p, the expected number of infested cherries shipped to Japan in a year from New Zealand would be 0.5. Thus, the probability of exporting one or more codling moth-infested cherries from New Zealand in a year is $1 - (1 - 1.54 \times 10^{-8})^{33,000,000}$, or 0.40. Depending on the export date, the most likely stages to be present would be eggs, first, or second instar larvae. Although the stage

distribution model predicts that some larvae could reach fifth instar by harvest and these are included in the risk assessment, in reality, fruit infested with late-instar larvae would probably not pass through grading and sorting processes, due to severe deterioration of the fruit.

Over the last 3 yr, an average of 2153 million cherries per year have been shipped to Japan from the USA. Using an average infestation level of 1.54×10^{-8}, based on the USDA inspection data, and accounting for less than 100% detection of early instars during inspection, approximately 43 immature codling moths would be shipped per year. An average of 0.41 individuals would be expected in a consignment of 20.5 million cherries (the median daily shipment to Narita/Tokyo in 1999).

4.2.3. Probability of surviving transit to Japan

Although codling moth eggs and larvae may experience some mortality while in transit to Japan in cherries (see the section on Survival in cherry during storage and transit), it is difficult to estimate this effect, and no transit-induced mortality has been assumed in the model.

4.2.4. Survival in Japan

If infested fruit was shipped from New Zealand to Japan, survival would depend on disposal in an area where the codling moth larvae could complete development, pupate, emerge, mate and find new hosts after emergence. This involves an assessment of climatic suitability, host availability, and patterns of cherry marketing, sales, and fruit waste disposal in Japan.

4.2.4.1. Cherry marketing, sale, and disposal in Japan.
The following comments on the marketing and sale of cherries in Japan were provided by Ms. Hiroko Kani, Agricultural Assistant, APHIS-International Services, American Embassy, Tokyo, Japan. After customs clearance, agents of "Seiyu", one of Japan's largest supermarket chains, bring the shipments to their distribution centre in Tokyo, where they serve their 100 retail stores. The shipment is individually packed at the distribution centre, where the fruit is held at approximately 10°C. Approximately 5 cartons of cherries, individually packed, are brought to each store per day, where the temperature is approximately 20°C. The fruit is sold the same day. The average weight of the individual cherry packs is approximately 300 g. Additional comments provided by James Christie of Bryant Christie Inc., Seattle, Washington, USA, indicate that some cherries are put on display at retail outlets with very little repackaging, and that consumer purchases may range from 100 to 500 g, depending on how the retailers repackage the product. This suggests that a Japanese consumer may purchase up to 68 cherries at a time (at 7.4 g per cherry). With an extremely low infestation level, the probability of a consumer purchasing more than one infested cherry is virtually nil: therefore, a new infestation would have to occur from surviving moths purchased by different consumers and disposed of in different places, unless two or more infested fruit were culled out at the retail level and disposed of at the same time.

Where cherries are repackaged for sale, it is likely that some infested cherries, particularly those with late instar larvae, would be detected and removed. Hansen et al. (1999) found that cherries artificially infested with codling moth deteriorated quickly, with several genera of fungi invading the fruit. This caused significant larval mortality, and rendered fruit unfit for sale. If no repackaging occurs, it is possible that a cherry with an early stage of infestation could be purchased by a consumer. For the immature moth to survive, the purchaser would have to dispose of the infested fruit in an area where continued development would be possible (e.g., outside, rather than in household rubbish bins). In New Zealand, telephone surveys by MAF (Wigbout, 1991; Viggers, 1993) suggest that up to 30% of New Zealand residents may dispose of household organic waste in backyard gardens and compost heaps. This percentage is expected to be much lower in Japan, where more people live in urban settings. Roberts et al. (1998) assumed that the amount of infested fruit disposed of outside in Japan would be approximately 0.5% (range 0.1–1%). We assume this is appropriate for cherries infested with eggs or early instar larvae, where some infested fruit could be eaten. It is less likely that fruit infested with third, fourth, or fifth instar larvae would be eaten, and we assume that 2.5% of this fruit could be disposed of outside (range 0.25–5%).

4.2.4.2. Climate assessment – New Zealand to Japan.
The export season for New Zealand cherries begins in early December and extends through January. Thus, fruit from New Zealand would arrive in Japan at the beginning of the coldest part of the year (Fig. 4). Although diapause-state codling moth larvae are highly cold tolerant, they do not enter this resistant state while in the fruit. Most larvae shipped from New Zealand at that time would likely be in the early stages of development (see earlier life cycle description, and stage of development studies), before the ability to enter this cold-hardy state is reached. Temperatures of 10°C or above would be required in order for development to continue in Japan: otherwise, development would be arrested (CMISS, 1999).

Winter temperatures for 41 weather stations in Japan were assessed to determine the area of the country where codling moth larvae arriving in December and January could continue to develop. Monthly averages for all stations between 1961 and 1990 were obtained from the Global Historical Climate Network on-line data set (Vose et al., 1992). Daily values for 37 stations during the 1997–98 winter were obtained from the Global Surface Summary of the Day (1998) on-line data set.

At the start of the export period, the average daily maximum temperatures in Tokyo are just beginning to
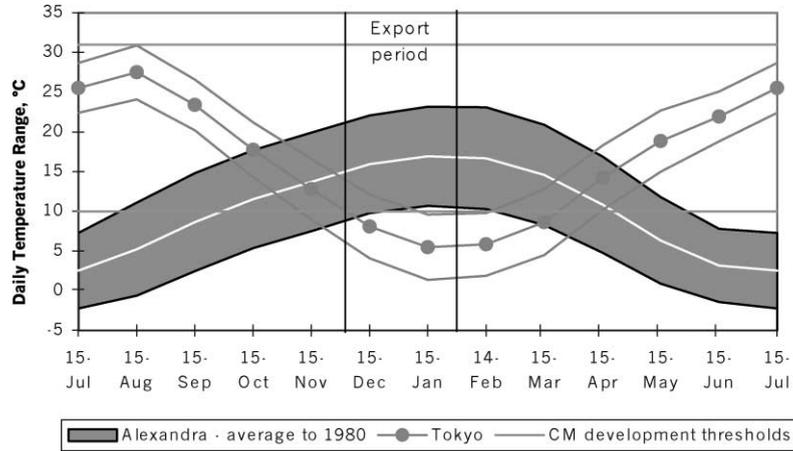
Fig. 4. Comparison of the average monthly temperature range in Alexandra, New Zealand (New Zealand Meteorological Service, 1983), with that of Tokyo, Japan. The upper and lower development thresholds for codling moth are shown as horizontal lines.
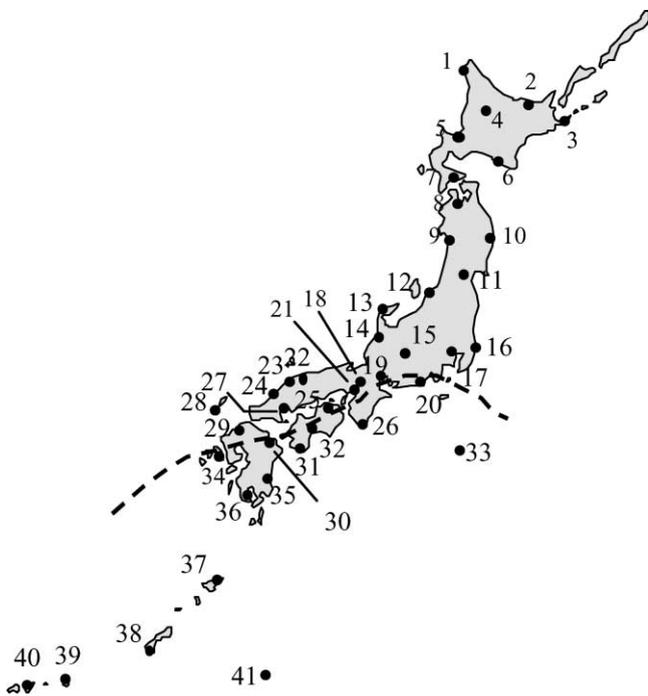

Fig. 5. Map showing the location of temperature stations assessed in Japan. Immature stages of codling moth in fruit disposed of outside north of the dotted line would not be expected to complete development. Temperature stations assessed are 1 Wakkanai, 2 Abashiri, 3 Nemuro, 4 Asahikawa, 5 Sapporo, 6 Urakawa, 7 Hakodate, 8 Aomori, 9 Akita, 10 Miyako, 11 Sendai, 12 Niigata, 13 Wajima, 14 Kanazawa, 15 Matsumoto, 16 Choshi, 17 Tokyo, 18 Kyoto, 19 Nagoya, 20 Omaezaki, 21 Osaka, 22 Yonago, 23 Matsue, 24 Hamada, 25 Takamatsu, 26 Shionomisaki, 27 Hiroshima, 28 Izuhara, 29 Fukuoka, 30 Oita, 31 Shimizu/Ashizuri, 32 Kochi, 33 Hachijojima, 34 Nagasaki, 35 Miyazaki, 36 Kagoshima, 37 Naze 38 Naha, 39 Miyakojima, 40 Ishigakijima, 41 Minamitaitojima.

drop to the 10°C threshold, indicating that little or no larval development could occur at ambient temperatures for several months. Immature stages of codling moth in fruit disposed of outside would not be expected to com-

plete development north of the line shown on the map (Fig. 5).

Prefectures where winter establishment of codling moth could occur are Kochi, Kumamoto, Miyazaki, Kagoshima, and Okinawa. The proportion of the population living in these prefectures is approximately 5.5%, based on the 1995 census figures (Statistics Bureau & Statistics Center Management and Coordination Agency, Government of Japan, 1999). If cherries are distributed around the country proportional to population, then approximately 5.5% could arrive in an area where the climate would permit continued development.

It is possible that some late-stage larvae could enter diapause on arrival in colder parts of Japan. As shown in Table 5, eggs laid early in the season in New Zealand could potentially reach fourth or fifth instar by harvest. Diapause larvae are resistant to cold and would be expected to survive winter conditions throughout Japan, based on conditions experienced elsewhere in their range. For the model, we make the assumption that fruit with eggs or first through third instar larvae would have a 5.5% chance of arriving in a region with a climate suitable for continued development, but this would increase to approximately 80% and 90% for fourth and fifth instar larvae, respectively, since fewer degree-days would be required for these stages to reach diapause.

4.2.4.3. Climate assessment – USA to Japan. Practically all of Japan would be favourable for all stages of codling moth which might arrive on cherries from the United States in late spring or summer, including host availability. The moth colonizes most temperate regions, wherever hosts are grown (see the section on Geographical distribution); thus we assume that 100% of the eggs and larvae would arrive in a region and climate suitable for continuing development.

4.2.4.4. Number of codling moth individuals expected to survive to reproductive age. Vail et al. (1993) suggested

Table 6
Model values for estimating the probability of establishment—winter-shipped cherries from New Zealand

	Eggs	1st	2nd	3rd	4th	5th
No. cherries shipped in a season (10 × average for last 5 years)			33,000,000			
No. consignments shipped in a season			28			
Observed proportion of cherries infested (average and upper 95th percentile)		1.54×10^{-8} (average)			2.50×10^{-8} (95th)	
Efficacy of inspection for detecting infestation	0.60	0.70	0.80	0.90	0.95	0.99
Proportion of individuals in stage at harvest (31 Jan, Blenheim)	0.08	0.36	0.26	0.13	0.09	0.08
Proportion of individuals surviving transit to Japan	1.0	1.0	1.0	1.0	1.0	1.0
Proportion of individuals missed by repackaging for sale	1.0	1.0	1.0	1.0	0.5	0.5
Proportion of individuals purchased and disposed of outside		—0.005 (0.001 − 0.01)—		—0.025 (0.0025 − 0.05)—		
Proportion of individuals arriving where climate suitable	0.055	0.055	0.055	0.055	0.80	0.90
Proportion of individuals surviving to adulthood	0.05	0.056	0.25	0.5	0.75	0.95
Probability of suitable hosts being present	1.0	1.0	1.0	1.0	1.0	1.0
Estimated number of individuals per consignment		2.5×10^{-2} (average)			3.8×10^{-2} (95th)	
Probability of at least one male and one female surviving from a consignment		3.2×10^{-10} (average)			8.5×10^{-10} (95th)	
Probability of at least one consignment having a male and a female survive		8.9×10^{-9} (average)			2.4×10^{-8} (95th)	

a value of 0.8 for the proportion of codling moths surviving from egg to adult in the absence of other mortality factors. Wearing et al. (1980, 1983) found that mortality of 1-, 3- and 5-d old codling moth eggs laid on cvs "Dawson" and "Bing" cherries (combined) was, respectively, 15.4, 13.4 and 9.8%. These figures suggest that overall survival from egg to adult could be significantly less than 0.8. This was confirmed by recent laboratory studies in which the highest survival from first instar to adult was 0.16 from "Chelan" cherries, and survival from four other cultivars was < 0.06 (Hansen, unpublished). Survival in field cages was even lower, with recovery of only three adult male moths or 0.0007 survival from the initial estimated population. The figure of 0.16 thus may represent a conservative estimate of the proportion of individuals likely to survive from egg to adulthood on cherries even under optimal conditions. The likelihood of surviving to adulthood would increase as immature development progressed. In the model, survival to adult was assumed to be 5% for eggs, 5.6% (Hansen, unpublished) for 1st instar larvae, 25% for 2nd instar larvae, 50% for 3rd instars, 75% for 4th and 95% for 5th.

4.2.4.5. *Host availability in Japan.* Virtually all of Japan's apple and non-Japanese pear production occurs outside the prefectures determined to be suitable for winter establishment of codling moth (cf. Japan MAFF Statistics, 1998 with Fig. 5 and associated text), as does 95% of the fruiting area and 97% of the production volume for Japanese pears. Of those prefectures likely to be climatically suitable, Kochi, Kumamoto, Miyazaki, and Kagoshima all have a small amount of apple and Japanese pear production, while Okinawa does not.

However, it seems probable that pome fruit trees will be scattered through the five prefectures in gardens and parks. In the absence of reliable data, we assume that host availability will not be a problem for surviving codling moths.

The probability of infested cherries being disposed of in a place where continued development and later infestation is possible (Ψ) is based on the estimates of Roberts et al. (1998) (see above). Using these estimates for the 5.5% of the fruit shipped to regions where the winter temperature on arrival would permit continued development, and assuming that suitable host trees are plentiful, the value of Ψ for eggs and early instar larvae is likely to be no more than 0.0003, and probably much lower. For third, fourth and fifth instar larvae, the value of Ψ would be 0.0014, 0.01, and 0.012, respectively.

Similar considerations of infested fruit disposal apply to cherries arriving in summer from the USA but regional temperatures and host availability are not predicted to limit the survival of codling moth. Thus, the expected value of Ψ would be 0.005 for eggs and early instar larvae, and 0.025, 0.0125 and 0.0125 for 3rd, 4th and 5th instars, respectively.

4.3. *Probability of establishment: winter-shipped cherries ex-New Zealand*

Table 6 lists the events necessary for codling moth establishment in Japan via New Zealand cherries, and shows the values used in the model. The infestation level was modelled as a beta distribution, with parameters of 12 and 777,442,688 (cherries infested/cherries uninfested). The probability of outside disposal was modelled with a beta

Table 7
Model values for estimating the probability of establishment — summer-shipped cherries from USA

	Eggs	1st	2nd	3rd	4th	5th
No. cherries shipped in a season (average for last 3 yr)			2,152,502,760			
Median daily consignment - Narita/Tokyo (1999)			20.52 million cherries			
No. such consignments in annual shipment			105			
Observed proportion of cherries infested (average and upper 95th percentile)		1.54×10^{-8} (average)			2.50×10^{-8} (95th)	
Efficacy of inspection for detecting infestation	0.60	0.70	0.80	0.90	0.95	0.99
Proportion of individuals in stage at harvest	0.10	0.35	0.25	0.10	0.10	0.10
Proportion of individuals surviving transit to Japan	1.0	1.0	1.0	1.0	1.0	1.0
Proportion of individuals missed by repackaging for sale	1.0	1.0	1.0	1.0	0.5	0.5
Proportion of individuals purchased and disposed of outside		——0.005 (0.001–0.01)——			——0.025 (0.0025–0.05)——	
Proportion of individuals arriving where climate suitable	1.0	1.0	1.0	1.0	1.0	1.0
Proportion of individuals surviving to adulthood	0.05	0.056	0.25	0.5	0.75	0.95
Probability of suitable hosts being present	1.0	1.0	1.0	1.0	1.0	1.0
Estimated number of individuals per consignment		0.44 (average)			0.65 (95th)	
Probability of at least one male and one female surviving from a consignment		5.4×10^{-7} (average)			1.4×10^{-6} (95th)	
Probability of at least one consignment having a male and a female survive		5.7×10^{-5} (average)			1.4×01^{-4} (95th)	

distribution having parameters of 4 and 800 (eggs, first and second instars) 5 and 200 (third–fifth instars). Other values were treated as point estimates, although they reflect the conservative (e.g., "worst-case") end of the spectrum.

The analysis produced distributions for the three outputs (expected number of codling moths present in a consignment, probability of a male and female surviving from a single consignment, and probability of a male and female surviving from at least one of the 28 consignments). A total of 3000 iterations of the model gave stable results for each output. The expected value (mean) and 95th percentile of the three distributions are also shown in Table 6.

The estimated number of individuals in a daily consignment of winter shipped cherries is expected to be no more than 0.038, with 95% confidence, while the probability of at least one male and one female surviving to adulthood from a consignment is not likely to exceed 8.5×10^{-10}. Thus, the probability of codling moth establishing in Japan from New Zealand cherries appears well-nigh impossible.

4.4. Probability of establishment: summer-shipped cherries ex-USA

The situation for cherries shipped to Japan in the summer differs from that for the winter-shipped cherries in one crucial respect: the climate of Japan in the summer would likely permit continued development of all arriving stages of codling moth.

It was estimated earlier that an average of 0.41 immature codling moths could be expected in the median daily shipment to Narita/Tokyo. We assume that at cherry harvest time, the proportion of immature codling moths in egg, first, second, third, fourth, and fifth instars are 10, 35, 25, 10, 10 and 10%, respectively. As with the winter-shipped cherries, conditions during transit to Japan would not be expected to cause appreciable mortality for any immature stages present. Upon arrival, shipments would be repackaged for sale, at which time we assume that any fourth or fifth instar larvae present would have a 50% probability of being detected, as with winter-shipped cherries.

Neither climate nor host availability would be expected to limit the establishment of codling moth from summer-shipped cherries. Survival of individuals to the adult stage is assumed to be no more than 5.6% for first instar larvae (Hansen, unpublished), ranging from 5% for eggs to 95% for 5th instar larvae (as for winter-shipped cherries).

Using values shown in Table 7, the simulation results show the expected number of individuals in the median daily Narita/Tokyo consignment of summer shipped cherries to be approximately 0.44, with an upper 95th percentile of 0.65. However, the probability of at least one male and one female surviving to adulthood from a consignment is much lower (95th percentile = 1.4×10^{-6}). With the annual US shipment equal to 105 consignments of the size of the Narita median daily shipment, the likelihood of a pair surviving from at least one

such consignment would be no greater than 1.4×10^{-4}, with 95% confidence. If we assume conservatively that the pair would be within calling range and mate (true probability would be $< 100\%$), this equates to no more than 1 outbreak expected per 6950 yr.

5. Conclusions

This review and analysis clearly demonstrates that quarantine measures against codling moth in sweet cherries are unnecessary for two reasons. There is unambiguous experimental evidence, supported by field observations, that sweet cherry is not a host of codling moth. This insect consistently rejects sweet cherry in the field (non-preference), even at high population densities, and when forced to feed on the fruit, low survival and slow development combine to make completion of the life cycle highly improbable. The isolated reports of codling moth in sweet cherry are so extremely rare that they provide no technical justification for including sweet cherry on quarantine host lists for codling moth. It is likely that at least some of these isolated reports are based on misidentifications. Larvae of few tortricids are easily identified to species level, and the tools available (e.g., dichotomous keys in unpublished circulars and published literature) frequently treat too few species, and hence, are inadequate. The wide array of similar-looking larvae make accurate determinations to the species level nearly an impossible task for the non-expert. Secondly, the risk of codling moth establishing in an overseas country such as Japan through the cherry trade has been shown to be extremely low for both USA and New Zealand cherries. The difference in risk estimates for cherries from the two countries is due to the much greater volume shipped from the USA and the winter conditions prevailing in Japan during the New Zealand cherry season. However, the risk estimates for both countries are sufficiently low that codling moth should not be considered a quarantine pest of export cherries. The extremely low risk derives primarily from the rarity of codling moth in export cherries and is further reduced by a variety of factors affecting distribution, survival, and establishment.

Acknowledgements

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