Crop Protection 129 (2020) 104994

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

A risk framework for using systems approaches to manage horticultural biosecurity risks for market access

Rieks D. van Klinken [a,*], Kathryn Fiedler [a], Lloyd Kingham [b], Kerry Collins [a], Darryl Barbour [c]

[a] CSIRO, GPO Box 2583, Brisbane, QLD, 4001, Australia
[b] Wagga Wagga Agricultural Institute, New South Wales Department of Primary Industries, PMB Pine Gully Road, Wagga Wagga, NSW, 2800, Australia
[c] Plant Health Australia, Level 1, Phipps Close, Canberra, ACT, Australia

ARTICLE INFO

Keywords:
Fruit fly
IPPC
Market-access
Pest risk assessment
Phytosanitary certification
Tephritidae
Trade
WTO

ABSTRACT

Phytosanitary 'Systems Approaches" comprise two or more independent, phytosanitary measures to reduce the risk of pest and pathogen movement through trade. They are increasingly being used to access markets for fresh fruit and vegetables. However, an overarching risk framework for assessing them is lacking. In this paper we first present an easily implementable risk framework for assessing systems approaches, and then test it through a retrospective analysis of publicly-available, systems-based protocols. Our risk framework is a matrix combining four risk reduction objectives with three production stages (pre-harvest, from harvest to phytosanitary certification and post-certification). The four risk reduction objectives, which explicitly focus on how measures reduce risk rather than how they are implemented, are: i) minimising exposure to pests when fruit are vulnerable; ii) minimising host vulnerability; iii) reducing infestation rate; and iv) reducing establishment likelihood. Of the 60 protocols sourced for our retrospective analysis, 52% targeted multiple pests (arthropods and pathogens) and 66% included fruit flies. The 327 measures included in those protocols (averaging 5.0 per protocol) were mapped against the risk framework, and were further categorised within each risk reduction objective according to how they reduce risk. Measures relating to administration or compliance, or ones considered as standard features in phytosanitary protocols, were excluded from analyses. All but two protocols had measures that addressed multiple combinations of risk reduction objectives and production stages. Most protocols (88%) combined measures that minimise pre-harvest exposure to the pest and measures that reduce infestation rates between harvest and certification. Protocols targeting fruit flies were similar to other protocols in terms of which measures were included and how they were combined. One important limitation of our study was that the publicly-available documents we reviewed mostly focussed on implementation of protocols, and rarely explained how the measures contributed to risk reduction, either individually or in combination. Addressing this gap is a priority. Our risk framework for systems approaches provides a versatile basis for developing and assessing new and more innovative protocols, and can thereby help facilitate safer, and more open, trade of fresh produce.

1. Introduction

Global trade in fresh fruit and vegetables is increasing (Diop and Jaffee, 2005), which imposes further risk of spreading injurious agricultural pests such as invertebrates and pathogens (Perrings et al., 2005). The International Plant Protection Convention (IPPC) is a legally-binding agreement governed by the Commission on Phytosanitary Measures to facilitate international movement and trade of plants and plant products, while minimising the risk of spreading plant pests (https://www.ippc.int). Four options for securing market access are recognised by the IPPC (Follett and Neven, 2006; IAEA, 2011). They are: i) non-host status of the commodity as traded (FAO, 2016a; Jang, 2016); ii) demonstrating the pest is not present (area freedom) (FAO, 2016b, 2017b); iii) a single post-harvest phytosanitary treatment (single-point treatments) (FAO, 2018, 2019); and iv) combining two or more, independent risk-reducing management measures that cumulatively achieve the appropriate level of phytosanitary protection (i.e. *systems approaches*) (FAO, 2016b, 2017c; Heather and Hallman, 2008). Where measures are independent a failure in one measure will not affect the operation of other independent measures (IAEA, 2011).

Systems approaches were developed to support horticultural exports in the mid-1980s (Jang and Moffitt, 1994; see Jones, 1983), were

* Corresponding author.
E-mail address: Rieks.vanklinken@csiro.au (R.D. van Klinken).

https://doi.org/10.1016/j.cropro.2019.104994
Received 29 June 2019; Received in revised form 17 October 2019; Accepted 26 October 2019
Available online 31 October 2019

adopted as an International Standard for Phytosanitary Measures (ISPM) in 2002 (FAO, 2017c) and are currently used to facilitate trade (IAEA, 2011; Jang, 2016). The single-point treatments commonly used for risk mitigation can cause phytotoxic damage to fruit (Jobling et al., 2002; O' Loughlin and Ireson, 1977), reduce shelf-life (Jobling et al., 2002; Thang et al., 2016), contribute to ozone depletion (APVMA, 2007; Jang, 2016; Thang et al., 2016), and can be unnecessarily restrictive for rarely infested commodities (Follett and Neven, 2006; Landolt et al., 1984). Although systems approaches have the potential to address many of these drawbacks, their application remains limited (Jamieson et al., 2014). A major issue is the lack of an agreed methodology for assessing risk against alternative protocols (Holt et al., 2018), although various methods have been proposed (Jamieson et al., 2014; Mengersen et al., 2012; Quinlan et al., 2016; Yamamura and Katsumata, 1999). In addition, a framework for understanding how individual measures contribute to risk reduction has not yet been developed.

Understanding how individual measures contribute to risk reduction is important for determining how they combine to reduce overall risk. To date, measures have been classified according to the production stage at which they are applied, rather than being explicit about how they reduce risk. Jang (2016), in a refinement of an earlier classification (Jang and Moffitt, 1994), organised measures against three production stages: pre-harvest, post-harvest, and what they referred to as "marketing and distribution". This approach to classifying measures according to production stages has been widely adopted in various formats (Dominiak, 2019; FAO, 2017c; IAEA, 2011; Podleckis, 2007). It does have the advantage of aligning measures against how they are to be implemented within a protocol. However, it doesn't provide insights into how measures actually reduce risk. Different measures within a production stage can reduce risk in quite different ways. In the pre-harvest stage, for example, measures might reduce the likelihood of fruit becoming infested, by limiting exposure of fruit to the pest, or only allowing the protocol to be applied to less susceptible cultivars.

Qualitative modelling has been proposed to assess the combined effect of all measures and their interactions across the entire production chain (Jamieson et al., 2016; Quinlan et al., 2016). Holt et al. (2018) conducted a comprehensive case study to examine the combined effect of all potential measures (or combinations thereof) on the predicted level of "pest infestation" at successive control points. In this study, measures are grouped according to production stage, rather than by how they reduce risk. As a result, measures that reduce risk in very different ways (e.g. prevent reinfestation or removing symptomatic fruit) are combined under a single control point. The risk-reduction functions of each measure are not specifically discussed, although they are implied through their influence on "infestation rates".

Quantitative risk assessments have been proposed to determine how measures combine to reduce overall risk within a systems approach (Baker et al., 1990; Moore et al., 2016; Yamamura and Katsumata, 1999). Baker et al. (1990) proposed the setting of a maximum pest limit as a way to manage the risk posed by exotic fruit flies, by ensuring sufficient individuals to establish a population would not occur. This concept was subsequently applied to a case-study where fruit infestation data from areas under contrasting pest management regimes were used (Mangan et al., 1997). Other studies focus on the effect of post-harvest measures on existing infestation rates within the fruit. For example, Jang (1996) calculated sequential mortality of fruit flies in avocados, taking into account natural mortality and heat treatment. Yamamura and Katsumata (1999) determined the effect of disinfestation treatment and subsequent export sampling inspection of the consignment (whilst taking pest biology and reproduction strategy into account) on "probability of introduction". The most comprehensive quantitative analysis is conducted by Moore et al. (2016), where empirical data were used to estimate the proportion of fruit packed for export that could be infested when incorporating several pre and post-harvest measures.

In this paper we present an easily implementable, risk assessment framework for creating and evaluating systems approaches. We then test its utility against publicly available protocols that are based on systems approaches. That includes using the risk framework to provide an overview of how risk-reducing measures have historically been combined within a systems approach, as a basis for future development of the discipline. Many of the protocols we reviewed targeted a diverse range of pests (arthropods and pathogens), which may lead to overestimating their complexity. We therefore also looked specifically at measures applied for fruit flies (Diptera: Tephritidae) to get a better understanding of how measures were combined to address a single threat. Fruit flies are high risk pests that have been the focus of considerable research (FAO, 2016a; Jang, 2016) and were a focus in many of the protocols we reviewed. The primary purpose of this study was to help provide a more rigorous basis for qualitative and quantitative risk modelling by classifying measures according to how they contribute to risk reduction.

2. Materials and methods

2.1. Proposed risk framework

The primary goal of our analyses was to develop an easily implementable risk framework that clearly describes how measures contribute to risk reduction. When developing the risk framework we consulted both the literature and Australian risk assessment professionals to maximise alignment with published concepts and terminologies.

Our risk framework consists of a matrix of four risk reduction objectives and three production stages (Fig. 1).

The four risk reduction objectives reduce risk in contrasting ways. *Minimising exposure to pests* can be achieved by ensuring pest densities are low at a time when fruit are vulnerable, or by preventing pest access to the fruit (such as through protected cropping). *Minimising host vulnerability* to being infected or infested relates to properties of the fruit that make it less likely to be affected, even if pests were present. These two risk reduction objectives determine the likelihood that fruit will be infested. Measures that *reduce infestation rates* typically involve killing or removing pests, but may include sterilisation or inactivation of the pest such that it no longer poses a threat. It could in theory be achieved at any production stage, once fruit has become infested. *Reducing establishment risk* can be achieved by imposing export conditions that reduce the risk of pest establishment in the event that arriving fruit were infested by live individuals.

We adapted the three production stages where risk reduction

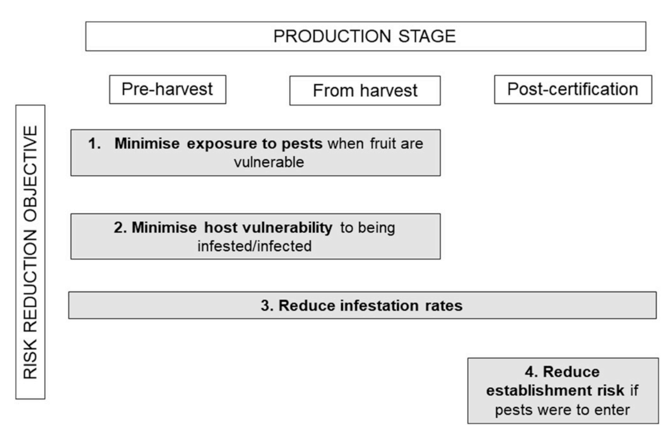

Fig. 1. Risk reduction framework proposed for systems approaches showing the four risk reduction objectives applied against the three production stages. Independent measures within a systems approach can be directed at one or more (but usually at least two) combination/s of risk reduction objective and production stage. Minimising exposure to pests from harvest to certification reduces risk of reinfestation.

objectives can be applied (see Fig. 1) from those presented by Jang (2016) and others. Harvest and post-harvest phases were combined because measures applied in these two stages often have similar objectives (e.g. removal of symptomatic fruit). Phytosanitary certification was used as a transition point, as the National Plant Protection Organization (NPPO) of the exporting jurisdiction normally has little or no direct oversight after this.

2.2. Sourcing systems approach protocols

Internet searches were conducted to locate all protocols that mentioned "systems approach" and were relevant to horticultural crops. That included searches of news sources that mentioned protocols, as a starting point to trace original documentation. To qualify, protocols needed to include at least two measures for at least one of the targeted arthropod or pathogen taxa. Protocols were only included if the primary source (government documents and scientific and industry literature) was publicly available, with the most recent version being used when possible.

Protocol attributes recorded were citation, commodity, date implemented or most recently updated, country of origin and destination, target pests, inclusion of fruit flies, and all details relating to required measures (Table A1).

2.3. Assigning measures within the risk framework

For each measure within each protocol we recorded a description of the measure and assigned it to a risk objective and production stage (Fig. 1). Within each risk reduction objective measures were grouped further according to how risk reduction was intended (see Results section). In some cases, how measures contributed to reducing risk had to be inferred from knowledge of the pest and system in question. If a single measure addressed multiple risk-reduction objectives or production stages, they were entered separately against each. Where protocols provided a choice between measures, then it was counted as one measure when determining the number of measures within a protocol, but as multiple measures when analysing the type of measures that were being used.

For measures that involved pest monitoring, we recorded the goal of monitoring (such as demonstrating pest freedom or low pest prevalence), and the consequence if a tolerance level was exceeded (e.g. a corrective action or rejection of the registered production block).

Activities were not included in our analyses of systems approach measures if: i) it was not clear how application of the measure would reduce risk; ii) they were also commonly included in protocols that don't rely on systems approaches ("standard measures"); or iii) they were not monitored or controlled by the responsible NPPO (FAO, 2017c).

2.4. Analyses

Protocols often addressed multiple pest threats. We therefore summarised protocol information according to whether protocols addressed only arthropods, only pathogens, or both arthropods and pathogens. We also tested whether the number of measures per protocol differed between commodities. Analyses were done for all targeted pests, as well as just for protocols and measures targeting fruit flies.

We classified measures according to how they contributed to risk reduction objectives. The total number of times that each measure was recorded against each risk-reduction objective and production stage was calculated, as was the proportion of protocols that each measure occurred in. The analysis did not include exempted measures (see Section 2.3), which were summarised separately.

How measures were combined into a systems approach was assessed by calculating the percentage of protocols which addressed each possible combination of risk reduction objectives and production stages.

3. Results

3.1. Overview of protocols

Sixty protocols were included in the analysis (Table A1) with an average of 5.0 measures per protocol overall (Table 1). About half (52%) of the protocols managed risk of multiple pests (Table 1). Three protocols only targeted pathogens. Fruit flies were included in 40 protocols (66%), with 21 protocols only targeting fruit flies. Fruit fly protocols also commonly targeted multiple fruit fly species (up to 10) (Table 1).

Protocols included between 2 and 13 measures (average of 5.0), while protocols only targeting fruit flies included between 2 and 7 measures (average of 4.8) (Table 1). Protocols targeting pathogens, and both pathogens and arthropods, had on average more measures (6.0 and 5.6, respectively) than those just targeting arthropods (4.7).

In total 18 fruit commodities were addressed by protocols. Five commodities were supported by more than two protocols (Table 1). The number of measures per protocol didn't differ greatly between these, with an average of 4.0–6.0 (Table 1).

3.2. Alignment of measures against our proposed risk framework

The 327 measures we identified could be readily assigned to one of the four risk reduction objectives and three production stages (Table 2).

In the 60 protocols we reviewed, risk reduction objectives (and their associated measures) applied to different production stages (Table 2). Measures aimed at minimising exposure to pests were mainly applied pre-harvest to manage in-field pest populations. Some measures to minimise exposure to pests also helped prevent reinfestation after harvest, although most of these were classified as standard measures (Table 3). Measures that minimise host vulnerability were only applied pre-harvest, those reducing infestation rates were all applied from the point of harvest onwards, and those preventing establishment were only applied post-certification. A likely exception to this pattern is the use of spraying as a pre-harvest pest management measure (Table 2). We mapped it against minimising exposure to pests, although spraying to reduce pest pressure might also reduce infestation rates if it kills pests already on or in fruit. For example, systemic insecticides may kill adult insects as well as immature insects feeding within the fruit.

Measures to meet the risk reduction objective "**minimise exposure to pests**" were diverse (Table 2). We combined measures that demonstrate *pest freedom or low pest prevalence* under one category as the distinction wasn't always clear in available protocols (e.g. a zero-pest threshold during harvest doesn't necessarily require pest freedom). We distinguished between the application of pest freedom or low pest prevalence measures as they applied to registered places of production (which sometimes included a buffer around a farm) from those applied across a larger area (as is typical for pest free areas). Associated pest monitoring ranged from periodic inspections for pest presence to targeted trapping. We differentiated measures according to the consequence if pest monitoring thresholds were exceeded. Consequences were rejection from the protocol, the requirement for a corrective action such as cover sprays, or were unspecified. Sixteen protocols had multiple measures relating to either pest freedom or low pest prevalence. For example, under the protocol for the importation of fresh peppers from Peru into continental United States, production sites need to be determined pest-free for both *Neoleucinodes elegantalis* and *Puccinia pampeana* by a pre-harvest inspection, as well as demonstrate pest freedom for *Anastrepha fraterculus* and *Ceratitis capitata* through monitoring two months before export and until the end of harvest (7 CFR § 319, 2015).

If pests were present in the field then the risk of exposure may be minimised through *pest management, pest avoidance or pest exclusion*. A wide range of preventative measures can contribute to *pest management*, beyond what was applied as a corrective action. In reviewed protocols, measures ranged from being very prescriptive (e.g. removal of all fallen fruit) to general (e.g. implementation of Integrated Pest Management

Table 1
Summary of protocols based on systems approaches that were included in the analyses, against the targeted pest taxa. Exempted measures (as described in Section 2.3) are not included.

	All protocols	Pest group			Fruit flies		
		Arthropod only	Pathogen only	Both	Total	Fruit fly only	Combined
No. protocols	60	42	3	15	40	21	19
No. pest species							
Mean ± SE	4.2 ± 0.7	2.4 ± 0.4	1.7 ± 0.7	9.9 ± 1.6	4.9 ± 0.9	1.4 ± 0.2	8.7 ± 1.3
Range	1–21	1–14	1–3	2–21	1–10	1–4	1–10
No. single species protocols	29	27	2	0	16	16	0
No. measures/protocol ("multi-choice" measures only counted once)							
Mean ± SE	5.0 ± 0.3	4.7 ± 0.2	6.0 ± 3.0	5.6 ± 0.6	4.7 ± 0.3	4.8 ± 0.3	4.5 ± 0.4
Range	2–13	2–7	3–12	3–13	2–8	2–7	2–8
Mean no. measures/protocol for crop hosts with more than 2 protocols							
Citrus (15 protocols)	5.5	4.0	7.5	8.0	4.7	4.4	5.0
Solanaceae (11 protocols)	4.6	4.8	na	4.3	4.3	4.3	4.3
Pome fruit (7 protocols)	5.0	4.8	na	5.5	5.0	na	5.0
Avocado (5 protocols)	6.0	6.0	na	6.0	5.8	6.0	5.5
Mango (3 protocols)	4.0	5.0	na	3.5	3.0	5.0	2.0

(IPM) or presence of biological control agents). *Pest avoidance* was achieved through harvesting before pests became active or abundant, restricting the use of protocols to poor pest habitats, or limiting exposure of harvested fruit to the pest. Partial or complete *exclusion* of pests from the host was achieved by bagging individual fruit, protected cropping, or semi-secure or secure transportation from orchard to the pack-house.

Measures that contributed to the risk reduction objective **"minimise host vulnerability"** (irrespective of pest presence) were grouped under the poor host category. They were limited to restricting application of the protocol to varieties with *low host susceptibility* and *harvesting at poor host stage* (e.g. "mature green" fruit). These measures were relatively rare, occurring in 8–12% of protocols (Table 2).

The risk reduction objective **"reducing infestation rates"** in fruit was broadly achieved through the categories *selectively removing infested fruit*, *killing, inactivating or removing the pest from the fruit*, and through *inspection and rejection of a consignment* if pests exceed a detection threshold. *Removing infested fruit* could be achieved directly through removing fruit with evidence of pest presence (symptom grading), or indirectly by grading fruit on quality factors (e.g. maturity, colouration, hardness or damage), such that fruit at greatest risk of being infested are preferentially removed (quality grading). *Killing, inactivating or removing pests* from fruit could be achieved through a range of methods, including cleaning fruit (e.g. surface disinfection, removal of debris or plant parts), and chemical or physical treatment (e.g. fumigation, heat, cold or irradiation). Some physical or chemical treatments could be categorised as single-point treatments, but were included in this analysis if they were complemented by additional risk-reduction measures. *Inspection, and rejection* if infestation rates exceeded a threshold (typically zero pests detected within a specified sample size), could occur from point of harvest through to reaching the market. *Rejection* ranged from rejection of the affected consignment through to loss of market access for the season with conditions set for re-entry to the market. We differentiated between inspections that were directly associated with phytosanitary certification and those conducted before or after certification which are typically additional inspections.

Risk reduction objective measures that **"reduce establishment risk"** (assuming infected fruit were to arrive at market) all related to ensuring exports only occurred to regions where pests were not expected to establish. They were only included in 12% of protocols (Table 2).

Most protocols (82%) had measures relating to pre-harvest pest monitoring to demonstrate low pest prevalence or pest freedom at the registered place of production, while 88% had an inspect and reject measure associated with phytosanitary certification (Table 2). Minimising exposure to pests was also supported most often by field hygiene (31%) and chemical spraying (25%) prior to harvest, and excluding pests from harvested fruit prior to them reaching a secure pack-house (25%). Other than inspect and reject at certification, the most common measures aimed at reducing infestation rates were additional inspect and reject measures (25%), quality and symptom grading (23%) and surface cleaning of fruit (22%).

Measures targeting fruit flies (present in 40 protocols) were similar to those applied to protocols overall, although surface cleaning was rarely required (Table 2).

The application of measures were mandatory in most cases irrespective of actual or potential pest pressure. One exception was the use of chemical sprays for pest management. It was required to be applied on a calendar basis in 12 protocols, whereas in 3 protocols (always associated with areas of low pest prevalence) application was dependent on risk, as determined by monitoring data.

3.3. Activities not considered to be part of a systems approach

We excluded some measures from our analysis of systems approaches, even though they clearly contribute to pest risk reduction (Table 3). The most commonly excluded measures were:

- Administrative activities such as grower and facility registration, provision of a work plan, and issuance of a phytosanitary certificate. This also included compliance measures (such as auditing of spray records) aimed at ensuring that another measure (spraying for pest management) had been done. Inclusion of compliance measures would have also resulted in double-counting.
- Measures to help prevent reinfestation that are also commonly applied to protocols that don't rely on systems approaches. These included getting harvested fruit to a secure pack-house within 24 h, secure packaging, pest monitoring and management within the pack-house, and keeping protocol fruit in separate lines. For systems approach protocols these could be applied throughout the supply chain.

Eleven protocols included post-certification inspections of consignments, sometimes through biometric sampling. Although this activity would be risk-reducing (by eliminating infested consignments), we didn't consider it to be a measure as it was not "monitored and controlled by the responsible [exporting] NPPO" (FAO, 2017c).

3.4. Combinations of measures into a systems approach

Most protocols addressed 2–3 combinations of risk reduction objectives and production stage (Fig. 2). Only two protocols addressed a single combination. They both minimised exposure to pests prior to harvest through a combination of measures within the pest monitoring, pest exclusion and pest management categories. One multi-pest protocol addressed six combinations of risk reduction objectives and production

Table 2
Measures included in the reviewed protocols, classified according to our risk framework (Fig. 1). Measures were further grouped into categories under each risk reduction objective. The percentage and number of protocols that included each measure are provided for all protocols as well as for protocols that have measures targeting fruit flies.

Risk reduction objective	All protocols (n = 60)				Protocols that include fruit flies (n = 40)			
	% Protocols	Production stage			% Protocols	Production stage		
Measures (grouped into categories)		Pre-harvest	From harvest	Post-certification		Pre-harvest	From harvest	Post-certification
Minimise exposure to pests								
Pest freedom or low pest prevalence (site)	82%				73%			
Pest monitoring + corrective action	30%	19			30%	12		
Pest monitoring + reject	37%	28			35%	15		
Pest monitoring + consequence unspecified	25%	17			18%	9		
Pest freedom or low pest prevalence (region)	15%				13%			
Pest monitoring + reject	15%	10			13%	6		
Pest management	62%				60%			
Spraying (calendar)[a]	20%	16			23%	13		
Spraying (risk-based)[a]	5%	3			3%	1		
Field hygiene	31%	26			38%	19		
Integrated Pest Management	13%	8	2		5%	2		
Biological control	3%	2			5%	2		
Pest avoidance	21%				28%			
Production in poor pest habitat	8%	5			13%	5		
Limit phenological overlap	10%	6			15%	6		
Limit exposure time to pest	8%		5		8%		3	
Pest exclusion	48%				45%			
Bagged fruit	7%	4			8%	3		
Glasshouse production	15%	9			20%	8		
Segregation and safeguarding	25%		16		33%		14	
Minimise host vulnerability								
Poor host	20%				15%			
Low host susceptibility	12%	7			5%	2		
Poor host stage at harvest	8%	5			13%	5		
Reduce infestation rates								
Kill/remove pest from fruit	43%				33%			
Heat	8%		5		10%		4	
Cold	7%		2	2	5%		1	1
Irradiation	3%		2		5%		2	
Methyl Bromide	5%		4		8%		4	
Postharvest agrochemical application	12%		9		5%		3	
Surface cleaning	22%		15		3%		1	
Remove infested fruit	25%				23%			
Quality grading	5%		3		5%		2	
Symptom grading	8%		5		3%		1	
Quality and symptom grading	23%		14		18%		7	
Inspect and reject "consignment"	88%				88%			
Inspect and reject (certification)[b]	87%		52		83%		33	
Inspect and reject (non-certification)	25%		16	2	23%		9	2
Reduce establishment risk								
Poor destination habitat	12%				8%			
Imported to poor pest habitat	12%			8	8%			4
Total number of measures		165	150	12		108	84	7

[a] Where in-field sprays also kill pests on or in the fruit then they may also reduce risk by reducing infestation rates in pre-harvest fruit. There was insufficient information available for most protocols to allow us to make this assessment.
[b] "Inspect and reject" measures were included in our analysis of systems approach protocols, although in some cases they could be considered as "standard practice" (see discussion).

stage. A similar pattern was observed for fruit flies (Fig. 2).

Most (88%) protocols combined measures that minimised exposure to pests at the pre-harvest stage with those that reduce infestation rates from the point of harvest (Table 4). Forty-six percent of all protocols only had that combination, with a further 17% also including the risk reduction objective minimising exposure to pests from the point of harvest (with measures targeting reinfestation).

Many of the protocols addressed a diverse range of pests (Table 1). By only looking at the protocols and measures directed at fruit flies we gained more insights into how risk reduction objectives are combined to address a specific threat. The combination of measures for fruit flies were similar to protocols overall (Table 4), although all fruit fly protocols included the risk reduction objective "minimise exposure to pests" at the pre-harvest stage.

4. Discussion

Phytosanitary measures are defined as activities that reduce the risk of pest introduction, spread and impact, which are applied or overseen by the relevant National Plant Protection Organization (NPPO) (FAO, 2017c). Measures have been previously grouped by production stage to describe their roles within a systems approach. Our risk framework adds to this by allowing them to also be categorised according to how they contribute to risk reduction. Retrospective analyses confirmed that our proposed risk framework was comprehensive as well as helpful in providing insights into how systems approach protocols have

Table 3
Standard measures (i.e. those that are also commonly included in protocols that don't rely on systems approaches) that were excluded from our analyses of systems approaches.

Risk-reduction objective		Preharvest	From harvest	Post-Certificate	Total
Measure category	Measure				
General					
Administrative					
	Registration	32	3		35
	Work plan provided	16			16
	Compliance inspection	11	5		16
Minimise exposure to pests					
Pest avoidance	Limited exposure to pest		15		15
Pest exclusion	Segregation and safeguarding		32	9	41
Reduce infestation rates					
Inspect and reject "consignment"					
	Inspect and reject (non-certification)		1	11	12
Total measures		59	56	20	135

historically been constructed. Our retrospective analyses highlighted considerable consistency in measures used, and how they were combined into a systems approach. Many protocols addressed multiple pests, both arthropods and pathogens. However, fruit flies were a target in two thirds of the protocols, highlighting that systems approaches are already being commonly applied to "high-risk" pests. Despite fruit fly's high-risk status (Jang, 2016), the types and combination of measures were similar to those used for protocols overall.

4.1. Comparison of our risk framework with existing classifications of measures

Our risk framework allows measures to be placed within a matrix of four risk reduction objectives and three production stages. The inclusion of risk reduction objectives allows for greater focus and scrutiny on how measures reduce risk. Application of this framework should assist in describing and modelling systems approaches. Bayesian networks have previously been developed to associate measures within a systems approach with production stages, but without systematically identifying how each individual measure reduces risk (Holt et al., 2018). We show that multiple risk reduction objectives can be addressed within a single production stage, and some risk reduction objectives can be applied at more than one production stage.

Our four risk reduction objectives (Fig. 1) and the categories of measures under each of those, broadly align with those previously discussed in the literature (e.g. see Follett and Neven, 2006; IAEA, 2011; Jang, 2016; Jang and Moffitt, 1994). Each risk reduction objective supports a protocol on its own, namely: pest free areas (minimising exposure to pests when fruit are vulnerable), non-host status (minimising host vulnerability), single-point treatments (reducing infestation rates) and limiting exports to where the pest is not able to establish (reduce establishment risk). However, systems approaches allow measures that address distinct risk reduction objectives to be combined.

4.2. Which measures belong in a systems approach?

Phytosanitary measures are clearly defined (FAO, 2017a), but our retrospective analyses of protocols identified some ambiguity regarding which measures are unique to systems approaches (as opposed to being standard practice for protocols more generally), and whether some are indeed measures. Without clarity there is a risk that most protocols could be considered as systems approaches. Clarity will also assist in the design of systems approaches, and assessment of their efficacy. Administrative measures, including compliance activities, are considered as dependent measures (IAEA, 2011). Nonetheless, we excluded them as they are not unique to systems approach protocols. We found a wide diversity of measures aimed at preventing reinfestation following harvest that are referred to as segregating and safeguarding measures in IAEA (2011). Some of these are standard requirements within protocols (such as getting fruit from harvest to a secure pack-house within 24 h). Targeted inspection of fruit consignments (with a consequence imposed if pests are found) is a common requirement when phytosanitary

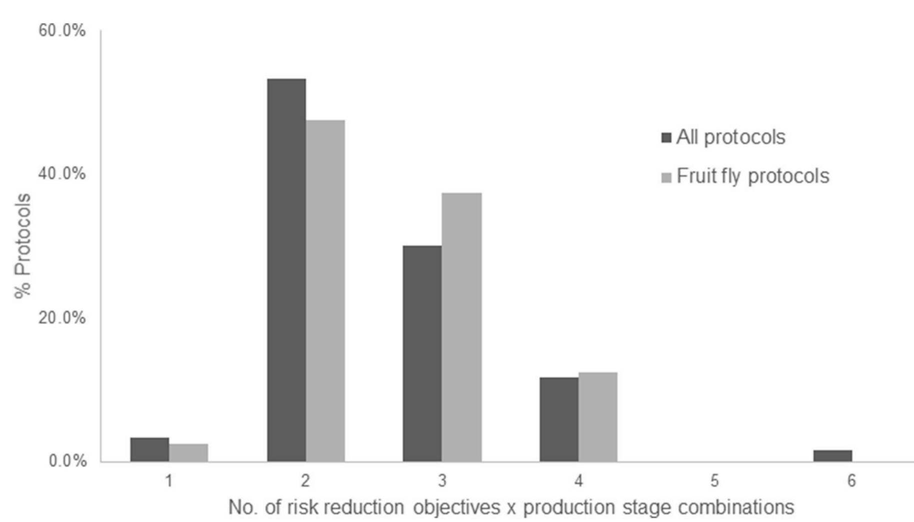

Fig. 2. The complexity of reviewed systems approach protocols (total and for those measures and protocols just directed at fruit flies) as indicated by the number of permutations of risk reduction objectives and production stages that measures addressed in each protocol.

Table 4
Combinations of risk reduction objectives and production stages addressed by measures within the reviewed protocols. Only the summary figures are provided for measures and protocols directed at fruit flies.

Protocols (% (no.))				Risk reduction objective grouped by production stage						
				Pre-harvest			From harvest		Post-Certification	
All		Fruit fly		Minimise exposure to pest	Minimise host vulnerability	Reduce infestation rates	Minimise exposure to pest	Reduce infestation rates	Reduce infestation rates	Reduce establishment risk
2%	(1)			y	y		y	y	y	y
7%	(4)	5%	(2)	y	y		y	y		
2%	(1)	3%	(1)	y	y			y	y	
2%	(1)	3%	(1)	y	y			y		y
5%	(3)	8%	(3)	y	y			y		
2%	(1)	3%	(1)	y		y				
18%	(11)	25%	(10)	y			y	y		
2%	(1)	5%	(2)	y			y			
2%	(1)			y			y			
2%	(1)	3%	(1)	y				y	y	y
2%	(1)	3%	(1)	y				y	y	
3%	(2)	3%	(1)	y				y		y
46%	(28)	40%	(16)	y				y		
3%	(2)	3%	(1)	y						
2%	(1)				y			y		y
2%	(1)							y		y
100%	(60)	100%	(40)							

certificates are issued, irrespective of whether or not it is a systems approach protocol. Our analyses included such inspections as measures within a systems approach, which could make it difficult to distinguish between protocols that rely on a systems approach and those based on single-point treatments where such measures may also be applied. Finally, there were two situations where stated measures may not meet the definition of phytosanitary measures. Pest monitoring in the absence of a corrective action would not constitute a measure as it doesn't reduce risk on its own. However, it is likely corrective actions were present but not mentioned in some protocols we reviewed. In contrast, inspection of consignments by the importer, with rejection if pests are found, would reduce risks. However, if the NPPO of the exporting country does not have oversight, we did not consider it to be a phytosanitary measure.

4.3. Types of measures being used

One benefit of systems approaches is that they allow risk-reducing activities that are already part of the production and supply chain to be formally recognised (IAEA, 2011; Jang and Moffitt, 1994), and can incorporate new technologies such as non-destructive detection of insects in fruit (Ekramirad et al., 2016). Use of measures in reviewed protocols were conservative, relying on measures that have already been well established and utilised in trade. Most were concerned with pest monitoring (with a consequence if a threshold was reached), field hygiene, calendar-spraying, and visual or biometric inspection of fruit. We found no protocols that utilised new technologies, such as in-line infra-red or optical scanning of fruit. Some risk-reducing activities, such as quality grading of fruit and exposing pests to postharvest conditions such as cold storage, are probably occurring, and can contribute to risk reduction (Moore et al., 2016), but were rarely included in the protocols we reviewed. Even though our study was restricted to publicly available protocols, it suggests room for considerable innovation in the types of measures that are incorporated into systems approaches.

Measures within a systems approach can be outcome based, for example where growers are given options as to how best to keep pest populations below a threshold (IAEA, 2011). This is also consistent with Integrated Pest Management (IPM) principles (Kogan, 1998). Indeed, the application and recognition of more flexible phytosanitary measures throughout the entire production and supply chain facilitates horticultural producers undertaking justified pest control measures, rather than potential indiscriminate use of pesticide and other control measures. Outcome-based measures were relatively rare among the protocols we reviewed. Only three protocols specified risk-based spraying and eight protocols specified integrated pest management. More common were protocols that required calendar-based spraying (12 protocols). Spray requirements varied, but could involve weekly sprays from when fruit were considered susceptible through to the end of harvest. Opportunities therefore exist to better reconcile systems approaches with IPM principles.

4.4. What combination of measures are typically used?

Current definitions of systems approaches require protocols to include at least two independent measures (FAO, 2017c; Jang, 2016). None of the reviewed protocols distinguished between dependent and independent measures in the available documentation. However, measures that address different risk reduction objectives can be expected to be independent, as failure in one should not affect the performance of another, even though the total level of protection may decrease. All but two protocols we reviewed met this "two risk reduction objectives" criterion. Both exceptions had several measures aimed at minimising pre-harvest exposure to pests. Measures addressing a single risk reduction objective within a production stage, such as successive mortality factors for pests in fruit, can be independent, although it can be difficult to demonstrate (Yamamura and Katsumata, 1999). Measures addressing a single risk reduction objective are often dependent on each other. For example, a suite of in-field pest management measures are commonly used to help ensure that pest monitoring thresholds are not exceeded. Most protocols we reviewed included an in-field pest monitoring measure (referred to as a "major independent component" in IAEA (2011), which was supported by one or more dependent measures to manage, avoid, or exclude pests.

A challenge for systems approaches is demonstrating how measures combine to reduce overall risk. Only occasionally did we find supporting quantitative risk analyses to show how different measures in the protocols we reviewed combined to reduce overall risk (Grové et al., 2010; Jang, 1996; Moore et al., 2016), although such analyses may have been done for other systems but not made public. Most protocols we reviewed combined measures to minimise exposure to pests with measures to reduce infestation rates. Quantitative risk modelling has so far focussed primarily on estimating the effect of measures on reducing infestation rates (Moore et al., 2016). Modelling the relationship between measures to reduce exposure to pests and infestation rate therefore remains an important gap, as does the data required to support such modelling.

Furthermore, some protocols we reviewed were complex, addressing all four risk reduction objectives and having multiple measures to address an individual risk reduction objective. A certain level of redundancy is desirable in the event that one measure fails (Follett and Neven, 2006), but we found no studies that address the question of how much redundancy is sufficient.

5. Conclusion

Our risk framework for systems approaches was able to show how all measures in our reviewed protocols contributed to reducing risk, and how they are typically combined within a systems approach. However, risk analyses that support these protocols were rarely made public. Sharing of these risk analyses would greatly benefit the ongoing development of systems approaches to support safe trade. Our analyses showed that protocols were relatively standard in terms of the types and combinations of measures used, suggesting considerable opportunities for further innovation in the development of systems approaches.

Funding

The project, Developing a national systems approach for meeting biosecurity requirements to access key Asian Markets, was funded by the Hort Frontiers Asian Markets Fund, and is part of the Hort Frontiers strategic partnership initiative developed by Hort Innovation, with co-investment from CSIRO, WA DPIRD, NSW DPI, Agriculture Victoria, and contributions from the Australian Government."

Declaration of competing InterestCOI

The authors declare that they have no conflicts of interest. This manuscript has not been published previously, also it is not under consideration for publication elsewhere. All authors approve this manuscript, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically.

Acknowledgements

We thank the many collaborators from the Australian Department of Agriculture, Agriculture Victoria, New South Wales Department of Primary Industries, Western Australian Department of Primary Industries and Regional Development, Hort Innovations and CSIRO for their conceptual contributions, and Andrew Robinson, Raphael Trouve, Ann Seitzinger, Airong Zhang and Penny Measham for reviewing earlier drafts of the manuscript.

Appendix

Table A1
Protocols used in the analysis and their source, as of June 2019.

Commodity Class	Country of Origin	Destination Country	Pest	Reference
Custard apple	Chile	USA (continental)	Arthropod	7 CFR § 319 (2018). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–82 Fresh cherimoya from Chile). https://www.regulations.gov/docket?D=APHIS-2015-0015
Custard apple	Australia (domestic trade)		Arthropod	ICA-18 (2017). Treatment and inspection of custard apple and other Annona Spp. Version 4. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2017/09/QLD-ICA-18.pdf
Pome	China	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–72 Apples from China). https://www.regulations.gov/docket?D=APHIS-2014-0003
Pome	New Zealand	Taiwan	Arthropod	Biosecurity New Zealand, 2011. MAF Phytosanitary Compliance Programme for the Export of Apples to Taiwan. Version 1 2011–2012. Ministry for Agriculture and Forestry, New Zealand, pp. 1–31. Biosecurity New Zealand, 2012. MAF Phytosanitary Compliance Programme for verification of the on-orchard pest management measures for codling moth (Cydia pomonella). Version 1.1 2011–2012. Ministry for Agriculture and Forestry, New Zealand, pp. 1–40.
Pome	New Zealand	China	Arthropod	Biosecurity New Zealand, 2011. MAF Phytosanitary Compliance Programme for the Export of Apples to China. Version 1 2011–2012. Ministry for Agriculture and Forestry, New Zealand, pp. 1–30 Biosecurity New Zealand, 2012. MAF Phytosanitary Compliance Programme for verification of the on-orchard pest management measures for codling moth (Cydia pomonella). Version 1.1 2011–2012. Ministry for Agriculture and Forestry, New Zealand, pp. 1–40.
Pome	South Korea	USA	Arthropod	7 CFR § 319 (2010). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–27 Apples From Japan and the Republic of Korea). https://www.regulations.gov/docket?D=APHIS-2009-0020
Pome	USA	Taiwan	Arthropod	Willett, M.J., Bishop, R., Jones, W., 2009. Systems Approach Work Plan for the Exportation of Apples from the US to Taiwan. Tree Fruit Research and Extension Centre (TFREC), Washington State University, Wenatchee, Washington. http://tfrec.cahnrs.wsu.edu/postharvest-export/wp-content/uploads/sites/3/2016/09/TaiwanSystemAppr_Packet16.pdf
Stone fruit	Spain (continental)	USA	Arthropod and Pathogen	7 CFR § 319 (2013). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–63 Fresh apricots from continental Spain). https://www.regulations.gov/docket?D=APHIS-2011-0132
Avocado	Colombia	USA (continental)	Arthropod	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–78 Hass avocados from Colombia). https://www.regulations.gov/docket?D=APHIS-2016-0022

(continued on next page)

Table A1 (*continued*)

Commodity Class	Country of Origin	Destination Country	Pest	Reference
Avocado	Hawaii	USA (continental)	Arthropod	7 CFR § 318 (2013). U.S. Code of Federal Regulations, Title 7, Part 318 (7 CFR § 318.13–20 Sharwil avocados from Hawaii to the continental United States). https://www.regulations.gov/docket?D=APHIS-2012-0008
Avocado	Mexico	USA	Arthropod and Pathogen	7 CFR § 319 (2016). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–30 Hass avocados from Mexico). https://www.regulations.gov/docket?D=APHIS-2014-0088
Avocado	Peru	USA (continental)	Arthropod	7 CFR § 319 (2010). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–50 Hass avocados from Peru). https://www.regulations.gov/docket?D=APHIS-2008-0126
Avocado	Spain (continental)	USA	Arthropod	7 CFR § 319 (2014). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–64 Avocados from continental Spain). https://www.regulations.gov/docket?D=APHIS-2012-0002
Banana	Philippines	USA (Continental)	Arthropod	7 CFR § 319 (2013). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–58 Bananas from the Philippines). https://www.regulations.gov/docket?D=APHIS-2011-0028
Berries	Australia (domestic trade)		Pathogen	ICA-31 (2016). Pre-harvest treatment and inspection for blueberry rust, Version 1. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2016/08/QLD-ICA-31.pdf ICA-31 (2017). Pre-harvest treatment and inspection of blueberries for blueberry rust, Version 3. Biosecurity & Food Safety, New South Wales Department of Primary Industries. https://www.interstatequarantine.org.au/wp-content/uploads/2017/07/NSW-ICA-31.pdf
Breadfruit	Fiji	New Zealand	Arthropod	Tirimaidoka, L., Waqa, N., Masamdu, R., 2007. Systems Approach to Improve Breadfruit Exports in Fiji, in: Ragone, D., Taylor, M.B. (Eds.), Proceedings 1st IS on Breadfruit Research and Development. Acta Hort 757, pp. 239–242.
Solanaceae	Australia (domestic trade)		Arthropod	ICA-26 (2019). Pre-harvest treatment and post harvest inspection of tomatoes, capsicums, chillies and eggplant, Version 7. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2019/02/QLD-ICA-26.pdf ICA-26 (2019). Pre-harvest treatment and post-harvest inspection of tomatoes, capsicums, chillies and eggplant, Version 10. Biosecurity & Food Safety, New South Wales Department of Primary Industries. https://www.interstatequarantine.org.au/wp-content/uploads/2019/03/NSW-ICA-26.pdf ICA-26 (2018). Pre-harvest treatment and post harvest inspection of tomatoes, capsicums, chillies and eggplant, Version 3. Western Australian Department of Primary Industries and Regional Development. https://www.interstatequarantine.org.au/wp-content/uploads/2018/05/WA-ICA-26.pdf
Citrus	Argentina	USA (continental)	Pathogen	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.28–56 Citrus from Argentina). https://www.govinfo.gov/content/pkg/FR-2000-06-15/pdf/00-14851.pdf
Citrus	Chile	USA (continental)	Arthropod	7 CFR § 319 (2004). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–38 Citrus from Chile). https://www.govinfo.gov/content/pkg/FR-2004-12-10/pdf/04-27075.pdf
Citrus	Mexico	USA (continental)	Arthropod	7 CFR § 319 (2005). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56). https://www.regulations.gov/docket?D=APHIS-2005-0027
Citrus	Peru	USA (continental)	Arthropod	7 CFR § 319 (201). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56). https://www.regulations.gov/docket?D=APHIS-2015-0005
Citrus	Australia (domestic trade)		Arthropod	ICA-28 (2012). Pre-harvest bait spraying and inspection of citrus. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2016/05/QLD-ICA-28.pdf
Citrus	South Africa	EU	Arthropod	Moore, S.D., Kirkman, W., Hattingh, V., 2016. Verification of Inspection Standards and Efficacy of a Systems Approach for Thaumatotibia leucotreta (Lepidoptera: Tortricidae) for Export Citrus From South Africa. Journal of Economic Entomology 109, 1564–1570.
Citrus	Texas	USA (limited)	Arthropod	Jang, E., Miller, C., Caton, B. (2015) Systems Approaches for managing the risk of citrus fruit in Texas during a Mexican Fruit Fly Outbreak. USDA. https://www.aphis.usda.gov/plant_health/plant_pest_info/fruit_flies/downloads/texas-citrus-systems-approach-risk-assesment.pdf
Citrus	Uruguay	China	Arthropod	Ares, M.I. (2012) Systems Approach: Concept and Application. 24° Technical Consultation among ORPF, August 2012. https://docs.google.com/presentation/d/16IochX0cziwqD50rH9Tp4buJhkSYqTnDBk-VsKEX1Tc/edit#slide=id.p1
Citrus	Uruguay	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2013). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–59 Fresh citrus fruit from Uruguay). https://www.regulations.gov/docket?D=APHIS-2011-0060
Citrus	Spain	USA	Arthropod	7 CFR § 319 (2002). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–34 Clementines from Spain). https://www.govinfo.gov/content/pkg/FR-2002-10-21/pdf/02-26668.pdf
Dragon fruit	Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama)	USA (continental)	Arthropod	7 CFR § 319 (2012). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–55 Fresh pitaya from certain Central American countries). https://www.regulations.gov/docket?D=APHIS-2010-0113
Dragon fruit	Ecuador	USA (continental)	Arthropod	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–77 Pitahaya from Ecuador). https://www.regulations.gov/docket?D=APHIS-2015-0004

(*continued on next page*)

Table A1 (*continued*)

Commodity Class	Country of Origin	Destination Country	Pest	Reference
Multiple Fruit	Australia (domestic trade)		Arthropod	ICA-21 (2017). Pre-harvest treatment and post-harvest inspection of approved host produce, Version 11. Biosecurity & Food Safety, New South Wales Department of Primary Industries. https://www.interstatequarantine.org.au/wp-content/uploads/2017/07/NSW-ICA-21.pdf
Gooseberry	Colombia	USA	Arthropod	7 CFR § 319 (2014). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–67 Cape gooseberry from Colombia). https://www.regulations.gov/docket?D=APHIS-2012-0038
Grapes	Australia (domestic trade)		Arthropod	ICA-20 (2017). Pre-harvest treatment and inspection of table grapes, Version 4. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2016/05/QLD-ICA-20.pdf
Kiwi	Chile	USA	Arthropod	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–53 Fresh kiwi and baby kiwi from Chile). https://www.regulations.gov/docket?D=APHIS-2014-0002
Citrus	Argentina (north west)	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–76 Lemons from northwest Argentina). https://www.regulations.gov/docket?D=APHIS-2014-0092
Citrus	Chile	USA	Arthropod	7 CFR § 319 (2018). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–38 Citrus from Chile). https://www.regulations.gov/docket?D=APHIS-2015-0051
Mango	Australia	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2013). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–60 Mangoes from Australia). https://www.regulations.gov/docket?D=APHIS-2011-0040
Mango	Australia (domestic trade)		Arthropod	ICA-19 (2014). Pre-harvest treatment and inspection of table grapes, 18. Northern Territory Government. https://www.interstatequarantine.org.au/wp-content/uploads/2016/05/NT-ICA-19.pdf
Mango	Vietnam	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–81 Fresh mango from Vietnam). https://www.regulations.gov/docket?D=APHIS-2016-0026
Citrus	Japan	USA	Arthropod and Pathogen	7 CFR § 319 (2014). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.28 Notice of quarantine (b)). https://www.regulations.gov/docket?D=APHIS-2013-0059
Citrus	Korea	USA (Alaska)	Arthropod and Pathogen	7 CFR § 319 (2007). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.28. Notice of quarantine (c)). https://www.regulations.gov/docket?D=APHIS-2006-0133
Citrus	Korea	USA (continental)	Pathogen	7 CFR § 319 (2007). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.28 Notice of quarantine). https://www.regulations.gov/docket?D=APHIS-2006-0133
Papaya	Central America and South America	USA (continental)	Arthropod	7 CFR § 319 (1998). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319 Papayas from Brazil and Costa Rica). https://www.govinfo.gov/content/pkg/FR-1998-03-13/pdf/98-6536.pdf
Papaya	Brazil, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Columbia, Ecuador	USA (continental)	Arthropod	7 CFR § 319 (2010). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–25 Papayas from Central America and South America). https://www.regulations.gov/docket?D=APHIS-2008-0050
Pome	China	USA	Arthropod and Pathogen	7 CFR § 319 (2013). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–57 Sand pears from China). https://www.regulations.gov/docket?D=APHIS-2011-0007
Solanaceae	Ecuador	USA	Arthropod and Pathogen	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–74 Peppers from Ecuador). https://www.regulations.gov/docket?D=APHIS-2014-0086
Solanaceae	Peru	USA (continental)	Arthropod and Pathogen	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–73 Peppers From Peru). https://www.regulations.gov/docket?D=APHIS-2014-0028
Persimmon	Japan	USA	Arthropod and Pathogen	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–79 Persimmons with calyxes from Japan). https://www.regulations.gov/docket?D=APHIS-2015-0098
Persimmon	New Zealand	USA	Arthropod and Pathogen	7 CFR § 319 (2017). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–80 Persimmons from New Zealand). https://www.regulations.gov/docket?D=APHIS-2015-0052
Pome	Australia (Tasmania)	Taiwan	Arthropod	– – (2013). Quarantine Requirements for the Importation of Fresh Apples from Australia. Australian Department of Agriculture, Forestry and Fisheries. https://micor.agriculture.gov.au/Plants/Protocols%20%20Workplans/Taiwan%20-%20Apples%20Protocol.pdf
Pomegranate	Chile	USA (continental)	Arthropod	7 CFR § 319 (2012). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–56 Fresh pomegranates from Chile). https://www.regulations.gov/docket?D=APHIS-2010-0024
Stone fruit	USA	Japan	Arthropod	USDA (2009). Systems Approach Approved for U.S. Cherries. Gain Report Number: JA9056. Global Agricultural Information Network, USDA Foreign Agricultural Service. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/STONE%20FRUIT%20ANNUAL_Tokyo_Japan_8-7-2009.pdf
Berries	Australia (domestic trade)		Arthropod	ICA-34 (2013). Pre-harvest field control and inspection of strawberries. Biosecurity Queensland, Queensland Department of Agriculture and Fisheries. https://www.interstatequarantine.org.au/wp-content/uploads/2016/05/QLD-ICA-34.pdf
Solanaceae	Ecuador	USA (continental)	Arthropod and Pathogen	

(*continued on next page*)

Table A1 (*continued*)

Commodity Class	Country of Origin	Destination Country	Pest	Reference
				7 CFR § 319 (2018). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–83 Tree tomatoes from Ecuador). https://www.regulations.gov/docket?D=APHIS-2015-0072
Solanaceae	Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama	USA	Arthropod	7 CFR § 319 (2006). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56-2dd Administrative instructions: conditions governing the entry of tomatoes). https://www.regulations.gov/docket?D=APHIS-2006-0009
Solanaceae	Chile	USA (continental)	Arthropod	7 CFR § 319 (2018). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–28 Tomatoes from certain countries (d)). pp 336–338.
Solanaceae	France	USA	Arthropod	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR §319.56–28 Tomatoes from certain countries (b)). pp 334-335
Solanaceae	South Korea	USA	Arthropod	7 CFR § 319 (2011). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–52 Tomatoes with stems from the Republic of Korea). https://www.regulations.gov/docket?D=APHIS-2010-0020
Solanaceae	Spain, Morocco, Western Sahara	USA	Arthropod	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–28 Tomatoes from certain countries (c)). pp 335-336
Solanaceae	West African States	USA	Arthropod	7 CFR § 319 (2015). U.S. Code of Federal Regulations, Title 7, Part 319 (7 CFR § 319.56–28 Tomatoes from certain countries (h)). pp 341-342
Solanaceae	New Zealand	Thailand	Arthropod	– – (2017). Importing Countries Phytosanitary Requirements – Thailand. Ministry for Primary Industries, New Zealand. https://www.mpi.govt.nz/dmsdocument/695/loggedIn

References

APVMA, 2007. Final Review Report and Regulatory Decision : the Reconsideration of Registrations of Products Containing Methyl Bromide and Their Associated Approved Labels, Review Series, vol. 6. Australian Pesticides and Veterinary Medicines Authority, Canberra.

Baker, R.T., Cowley, J.M., Harte, D.S., Frampton, E.R., 1990. Development of a maximum pest limit for fruit flies (*Diptera: Tephritidae*) in produce imported into New Zealand. J. Econ. Entomol. 83, 13–17.

7 CFR § 319, 2015. U.S. Code of federal regulations, title 7, Part 319 (7 CFR §319.56-73 peppers from Peru). https://www.regulations.gov/docket?D=APHIS-2014-0028.

Diop, N., Jaffee, S.M., 2005. Fruits and vegetables: global trade and competition in fresh and processed product markets. In: Aksoy, M., Beghin, J. (Eds.), Global Agricultural Trade and Developing Countries. The World Bank, Washington, DC, pp. 237–257.

Dominiak, B.C., 2019. Components of a systems approach for the management of Queensland fruit fly *Bactrocera tryoni* (Froggatt) in a post dimethoate fenthion era. Crop Protect. 116, 56–67.

Ekramirad, N., Adedeji, A.A., Alimardani, R., 2016. A review of non-destructive methods for detection of insect infestation in fruits and vegetables. Innov. Food Res. 2, 6–12.

FAO, 2016. Determination of Host Status of Fruit to Fruit Flies (Tephritidae). International Standard for Phytosanitary Measures No. 37. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 14.

FAO, 2016. Phytosanitary Principles for the Protection of Plants and the Application of Phytosanitary Measures in International Trade. International Standard for Phytosanitary Measures No. 1. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 14.

FAO, 2017. Glossary of Phytosanitary Terms. International Standard for Phytosanitary Measures No. 5. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 34.

FAO, 2017. Requirements for the Establishment of Pest Free Areas. International Standard for Phytosanitary Measures No. 4. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 9.

FAO, 2017. The Use of Integrated Measures in a Systems Approach for Pest Risk Management. International Standard for Phytosanitary Measures No.14. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 12.

FAO, 2018. Requirements for the Use of Temperature Treatments as Phytosanitary Measures. International Standard for Phytosanitary Measures No. 42. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 14.

FAO, 2019. Requirements for the Use of Fumigation as a Phytosanitary Measure. International Standard for Phytosanitary Measures No. 43. Published by FAO on Behalf of the Secretariat of the International Plant Protection Convention. IPPC, Rome, p. 18.

Follett, P.A., Neven, L.G., 2006. Current trends in quarantine entomology. Annu. Rev. Entomol. 51, 359–385.

Grové, T., De Beer, M.S., Joubert, P.H., 2010. Developing a systems approach for *Thaumatotibia leucotreta* (*Lepidoptera: tortricidae*) on 'Hass' avocado in South Africa. J. Econ. Entomol. 103, 1112–1128.

Heather, N.W., Hallman, G.J., 2008. Pest Management and Phytosanitary Trade Barriers. Cabi Publishing.

Holt, J., Leach, A.W., Johnson, S., Tu, D.M., Nhu, D.T., Anh, N.T., Quinlan, M.M., Whittle, P.J.L., Mengersen, K., Mumford, J.D., 2018. Bayesian networks to compare pest control interventions on commodities along agricultural production chains. Risk Anal. 38, 297–310.

IAEA, 2011. FAO/IAEA Guidelines for Implementing Systems Approaches for Pest Risk Management of Fruit Flies - Working Material. FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna, Austria, 7 - 11 June 2010.

Jamieson, L.E., DeSilva, H.N., Worner, S.P., Rogers, D.J., Hill, M.G., Walker, J.T.S., 2014. A review of methods for assessing and managing market access and biosecurity risks using systems approaches. N. Z. Plant Prot. 66, 1–9.

Jamieson, L., Woodberry, O., McDonald, C., Ormsby, M., 2016. Developing a generic biosecurity risk assessment model for imports. N. Z. Plant Prot. 69, 186–199.

Jang, E.B., 1996. Systems approach to quarantine security: postharvest application of sequential mortality in the Hawaiian grown 'sharwil' avocado system. J. Econ. Entomol. 89, 950–956.

Jang, E.B., 2016. Systems approaches for managing the phytosanitary risk of trading in commodities that are hosts of fruit flies. In: Ekesi, S., Mohamed, S., de Meyer, M. (Eds.), Fruit Fly Research and Development in Africa - towards a Sustainable Management Strategy to Improve Horticulture. Springer International, pp. 737–751. Web.

Jang, E.B., Moffitt, H.R., 1994. Systems approaches to achieving quarantine security. In: Sharp, J.L., Hallman, G.J. (Eds.), Quarantine Treatments for Pests of Food Plants. Westview Press, Boulder, USA, pp. 225–237.

Jobling, J., Morris, S., James, H., 2002. Methyl Bromide Usage and Alternaatives for Disinfestation Treatments. Horticulture Australia Ltd, Sydney, pp. 1–135.

Jones, J.G.W., 1983. The case for a systems approach. In: Cavalloro, R. (Ed.), Proceedings of the CEC/IOBC International Symposium - Fruit Flies of Economic Importance, 1983, Athens, Greece 16-19 November 1982.

Kogan, M., 1998. Integrated pest management: historical perspectives and contemporary developments. Annu. Rev. Entomol. 43, 243–270.

Landolt, P.J., Chambers, D.L., Chew, V., 1984. Alternative to the use of probit 9 mortality as a criterion for quarantine treatments of fruit fly (*Diptera: tephritidae*)-infested fruit. J. Econ. Entomol. 77, 285–287.

Mangan, R.L., Frampton, E.R., Thomas, D.B., Moreno, D.S., 1997. Application of the maximum pest limit concept to quarantine security standards for the Mexican fruit fly (*Diptera: Tephritidae*). J. Econ. Entomol. 90, 1433–1440.

Mengersen, K., Quinlan, M.M., Whittle, P.J.L., Knight, J.D., Mumford, J.D., Wan Ismail, W.N., Tahir, H., Holt, J., Leach, A.W., Johnson, S., Sivapragasam, A., Lum, K. Y., Sue, M.J., Othman, Y., Jumaiyah, L., Tu, D.M., Anh, N.T., Pradyabumrung, T., Salyapongse, C., Marasigan, L.Q., Palacpac, M.B., Dulce, L., Panganiban, G.G.F., Soriano, T.L., Carandang, E., Hermawan, 2012. Beyond compliance: project on an integrated systems approach for pest risk management in South East Asia. EPPO Bull. 42, 109–116.

Moore, S.D., Kirkman, W., Hattingh, V., 2016. Verification of inspection standards and efficacy of a systems approach for *Thaumatotibia leucotreta (Lepidoptera: tortricidae)* for export citrus from South Africa. J. Econ. Entomol. 109, 1564–1570.

O' Loughlin, J.B., Ireson, J.E., 1977. Phytotoxicity of methyl bromide fumigation to a range of apple cultivars. Aust. J. Exp. Agric. 17, 853–858.

Perrings, C., Dehnen-Schmutz, K., Touza, J., Williamson, M., 2005. How to manage biological invasions under globalization. Trends Ecol. Evol. 20, 212–215.

Podleckis, E.V., 2007. Systems approaches as phytosanitary measures: techniques and case studies. In: Vreysen, M.J.B., Robinson, A.S., Hendrichs, J. (Eds.), Area-Wide

Control of Insect Pests: from Research to Field Implementation. Springer Netherlands, Dordrecht, pp. 417–423.
Quinlan, M.M., Mengersen, K., Mumford, J., Leach, A., Holt, J., Murphy, R., 2016. Beyond Compliance: A Production Chain Framework for Plant Health Risk Management in Trade. Chartridge Books, Oxford.
Thang, K., Au, K., Rakovski, C., Prakash, A., 2016. Effect of phytosanitary irradiation and methyl bromide fumigation on the physical, sensory, and microbiological quality of blueberries and sweet cherries. J. Sci. Food Agric. 96, 4382–4389.
Yamamura, K., Katsumata, H., 1999. Estimation of the probability of insect pest introduction through imported commodities. Res. Popul. Ecol 41, 275–282.