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ORIGINAL PAPER

A menu of measures to manage trade-related plant pest risks, and a review of methods for demonstrating measure efficacy

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Abstract Ever-increasing global trade is one of the most important introduction pathways for plant pests. A diverse range of risk-reducing measures can be applied depending on the pest, the commodity and the import requirements. We used a review of over 1,800 risk reduction measures to extend a risk framework and menu of measures, previously developed for horticulture, to be applied to any commodity. We also reviewed how the efficacy of risk reduction measures is demonstrated, and assessed the maturity of the supporting science. We identified 39 unique risk reduction measures that were classified according to how they reduce risk. These were grouped under ten measure categories and four risk reduction objectives (minimising exposure to pest, minimising vulnerability of the commodity, reducing infestation rate and reducing establishment risk). These could then be applied against one or more consignment stages (production, post-production and post-border). Measures covered both commercial activities that reduce risk and may contribute to pest risk assessment, and regulated measures mandated to address unrestricted risk. Almost 90% of citations included measures that minimised exposure to pests or reduced infestation. Some measures were rarely reported, and some commodity classes had few measures associated with them, suggesting that available measures are being underutilised. Clear guidance was apparent for demonstrating efficacy of some measures (e.g., kill treatments), but lacking for many others. Compiling a 'menu of risk reduction measures' according to how they reduce risk, accompanied by clear guidelines for demonstrating efficacy, provides a robust basis for agreement between jurisdictions, and the further development, refinement and communication of efforts to both assess and manage the risk of global, trade-related pest movement. Agreement on how efficacy can be demonstrated for less utilised measures identified in this study will contribute to the further development of risk-based trade.

Keywords Commodity · Pest risk analysis · Pest risk assessment · Phytosanitary Pests · Pest risk management

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Introduction

Global trade is a significant, ongoing cause of pest movement. Plant pests (including pathogens) are most often moved with their host (e.g., fruit, vegetables, cut flowers, timber, soil), or as contaminating pests (ISPM5, IPPC Secretariat 2017a) carried by a commodity or as stowaways associated with transport vectors such as wood packaging, container ships or machinery (Liebhold et al. 2006; Meurisse et al. 2019; Saccaggi et al. 2016; Turner et al. 2021). Hereafter, this broad range of traded articles will be termed commodities, which can include both hosts and carriers of pests. Pest Risk Analysis (PRA) is performed to identify pests and pathways of concern, determine the associated "unrestricted" risk of entry, establishment, spread and economic loss (pest risk assessment), and then identify pest risk management options to reduce the risk of introduction and spread (Devorshak 2012; EPPO 2011; ISPM11, IPPC Secretariat 2017d; EFSA PLH Panel et al. 2018; MacLeod and Baker 2003). PRA may consider features of production and the supply chain that reduce risk such as hygiene practices, quality grading and physical storage conditions. If the unrestricted risk is unacceptable then it can be designated as a regulated article with "phytosanitary measures" applied to manage that risk (Allen et al. 2017). To this end, a wide range of measures have been used or suggested to manage the risk of pest introduction or spread. Apart from a recent review of measures that were included in publicly available phytosanitary systems approaches (van Klinken et al. 2020), there have been few attempts to classify measures according to how they reduce risk. Further, international standards for demonstrating the efficacy of measures have focussed heavily on disinfestation treatments and have not yet been developed for some other widely used mitigation approaches (Follett and Neven 2006). Lack of harmonisation in trade regulation and standards can come at considerable cost to industry and regulators (Engler et al. 2012). A consistent classification, presented as a menu of possible measures (EFSA PLH Panel et al. 2018), together with guidance on how to demonstrate efficacy for each (Follett and Neven 2006; FAO 2016), would greatly assist in furthering the design, development and application of harmonised, risk-based trade as outlined under WTO Agreement on Sanitary and Phytosanitary Measures (World Trade Organization 1994).

Phytosanitary measures are defined within the International Standards for Phytosanitary Measures (ISPM) as legislation, regulation or official procedures to prevent the introduction or spread of quarantine pests (ISPM5, IPPC Secretariat 2017a). The minimum requirements for a *phytosanitary measure*, at least when considered within a phytosanitary systems approach, are that they are: (i) clearly defined; (ii) efficacious; (iii) officially required (mandatory); and (iv) can be monitored and controlled by the responsible National Plant Protection Organization (NPPO) (ISPM14, IPPC Secretariat 2017g). In this paper, we differentiate between "*phytosanitary measures*" and "*commercial measures*" which must be clearly defined and demonstrably reduce the risk of trade-related biosecurity threats (i.e., efficacious), but may not need to be officially mandated or monitored. In this sense, measures include characteristics, activities or processes that may already be features of the production system or supply chain and which contribute to risk reduction, intentionally or not. Where such measures are already standard production or supply chain practice they may be considered when undertaking a pest risk assessment. In some cases, these measures may be a commercial requirement for a commodity, for example through the establishment of industry-based production practices or buyer-driven private quality standards (Griffin 2012a). Phytosanitary measures applied to a regulated article therefore differ only by being officially required, formally notified, monitored and controlled by a relevant government agency or delegated authority. Whether a risk-reducing production practice requires this additional regulatory oversight may depend on its importance, and the level of confidence that it is already being consistently applied across the industry. For example, if production only occurs in areas where pest abundance is demonstrably low, then that aspect of production may be considered during the pest risk assessment, otherwise a phytosanitary measure may be required to limit trade to a commodity sourced from those areas.

A wide range of measures contribute, or are used, to manage biosecurity risks, and others have been suggested. These can be applied anywhere across the production system and supply chain. Lists of potential options are frequently provided (ISPM14 and IPPC Secretariat 2017g; EFSA PLH Panel et al. 2018; USDA 2002). However, measures are typically

grouped according to when they are applied (e.g., pre-harvest or post-harvest, or the specific control point), with little explicit consideration given to how they reduce risk. Understanding how measures reduce risk is important when it comes to identifying which combination of measures are needed to address unrestricted risk, and to quantify that effect (van Klinken et al. 2021). For some measures the evidence required to demonstrate efficacy is well established, for example to demonstrate the efficacy of widely used kill treatments such as fumigation and cold treatment (Heather and Hallman 2008). In contrast, utilisation of other measures may be limited by an apparent lack of guidance and agreement on how efficacy should be established (Follett and Neven 2006; Jang 2016; van Klinken et al. 2021; van Klinken et al. 2020).

A recent analysis of phytosanitary systems approaches classified the measures used according to how they reduce risk (van Klinken et al. 2020). It found that measures can reduce risk in one of four ways, by: (i) minimising exposure to the pest; (ii) minimising host vulnerability; (iii) reducing infestation rate; and (iv) minimising establishment risk. Measures were further classified under each of these four risk-reduction objectives. However, this study was restricted to existing phytosanitary measures used in publicly available systems approach protocols developed for trade in horticultural produce, and did not look at what evidence would be required to assess their efficacy.

Here we develop a comprehensive "menu of measures" that classifies measures according to how they reduce risk. We then assess how efficacy can be established for each of the measures and the maturity of the supporting science. The menu of measures is intended to support both pest risk assessment and pest risk management, or together in a PRA. We therefore did not distinguish between measures that are mandated by the NPPO (phytosanitary measures), are a commercial requirement (commercial measures), or existing features of the production or supply chain system that contribute to risk-reduction. Existing and potential measures relating to trade in any commodity or carrier relevant to the movement of plant pests were identified through a literature review. These measures were then classified according to how they reduce risk using the classification of van Klinken et al. (2020) as a starting point. Potentially underutilised measures were identified through an assessment of how often they were cited in the literature, and for what commodities they were being suggested. Literature relevant to demonstrating efficacy was then reviewed for each category of measure to identify where further effort may be required to establish agreed standards. We finish with a discussion on how the risk framework and "menu of measures" can be applied more broadly within a PRA to both help estimate unrestricted risk through pest risk assessment and determine how identified risks can best be managed.

Methods

Sourcing measures

Internet searches were conducted to locate any literature (journal papers, books, public reports, ISPMs) and publicly available protocols that discussed or listed measures relevant to the trade in commodities. We used commodity classes listed in ISPM 5 (IPPC Secretariat 2017a) as a starting point. Internet searches were conducted using a combination of keyword searches, including words such as "phytosanitary", "phytosanitary measures", "risk management", "biosecurity", "quarantine measures", along with the various commodity classes (e.g., seeds, plant in vitro and cut flowers). References cited in other key documents were also reviewed, as a form of snowball sampling to collect key documents. Webpages from key governments (e.g., USA) and organisation (e.g., Plant Protection Organisations) were also searched. The aim of the review was to identify the diversity of measures proposed or used to manage trade-related risks of plant pests. We therefore did not attempt to comprehensively source and review existing protocols where they were expected to rely on similar risk-reducing measures (such as single point treatments) or measures that were already captured in reviews. For measures to be included in the analysis it needed to be clear as to how they reduce risk. For each measure we recorded the citation, commodity class that it related to, where in the production system it is to be applied, and relevant descriptive details.

Assigning measures within the risk framework

Each identified measure was assigned to a measure category within a risk reduction objective, and the consignment stage to which it applies. These measures were initially classified into measure categories under each of four risk reduction objectives according to the risk framework van Klinken et al. (2020). Measure categories further classifies measures according to how they reduce risk under each risk reduction objective. How measures were defined and classified was then refined to accommodate the diversity of measures and commodities identified through the review. If the cited measure could reduce risk in multiple ways, then they were entered for each.

Analysis of reviewed measures

Once cited measures were classified against our risk framework then results were summarised by literature source to give an indication of their prevalence in the biosecurity literature and by commodity class. In each case the number of measure types and times measures were cited under each risk reduction objective was calculated. Commodity classes were adapted from ISPM 5 (IPPC Secretariat 2017a). For each commodity class the consignment stage at which infestation risk is greatest was also identified, the total number of references that identified measures were counted for each commodity class, and the key literature listed.

Evidence of efficacy

Literature was reviewed to determine what is broadly required to establish efficacy for each measure category, and to assess how well developed and agreed the supporting methodologies were. Level of development was qualitatively assessed as being high (supported by internationally agreed guidelines, or exemplar studies), moderate (some supporting studies on relevant aspects), low (only tangential studies) or variable (between measures within a measure category). Where there was limited information in the market access and biosecurity literature the review was extended to relevant literature in ecology, plant-insect and plant-pathogen interactions and pest management.

Results

Overview of measures found and the updated risk framework and menu of measures

Over 1,800 measures were reported in the surveyed literature. We classified an additional 179 activities as "administration and oversight" rather than measures. These included audit requirements, compliance inspections, registration, phytosanitary certification, provision of work plan, traceability (tracking/tracing) and record keeping.

We identified a total of 39 types of measures when classifying the reviewed measures according to how they reduce risk (Fig. 1). Some modifications to the measures and measure categories outlined in van Klinken et al. 2020 were required to allow the risk framework to be extended beyond horticulture, and to accommodate measures that were not identified in that study. The most significant changes are explained below.

Consignment stages against which measures can be applied

Consignments are traded articles covered (when required) by a single phytosanitary certificate (IPPC Secretariat 2017a). Here we use the term in a restricted sense to refer to a single commodity from a common origin. Measures to manage the risk of pest introduction and spread can therefore be applied to a consignment during production and throughout the supply chain. The three stages proposed by van Klinken et al. (2020) for where measures could be applied to manage risk in fruit (pre-harvest, from harvest and post-certification) needed modification to extend to commodities such as growing media and machinery. Furthermore, the point in the supply chain at which phytosanitary certification is conducted varies. We therefore altered the stages at which measures can reduce risk to the following three *consignment stages*:

- *Production*, which includes production of fresh produce ("pre-harvest"), nursery products and in vitro plants prior to being moved from the growing area, turf prior to being dug up, wood prior to trees being felled, and the manufacturing of growing media and wood packaging (when considered as a commodity class).

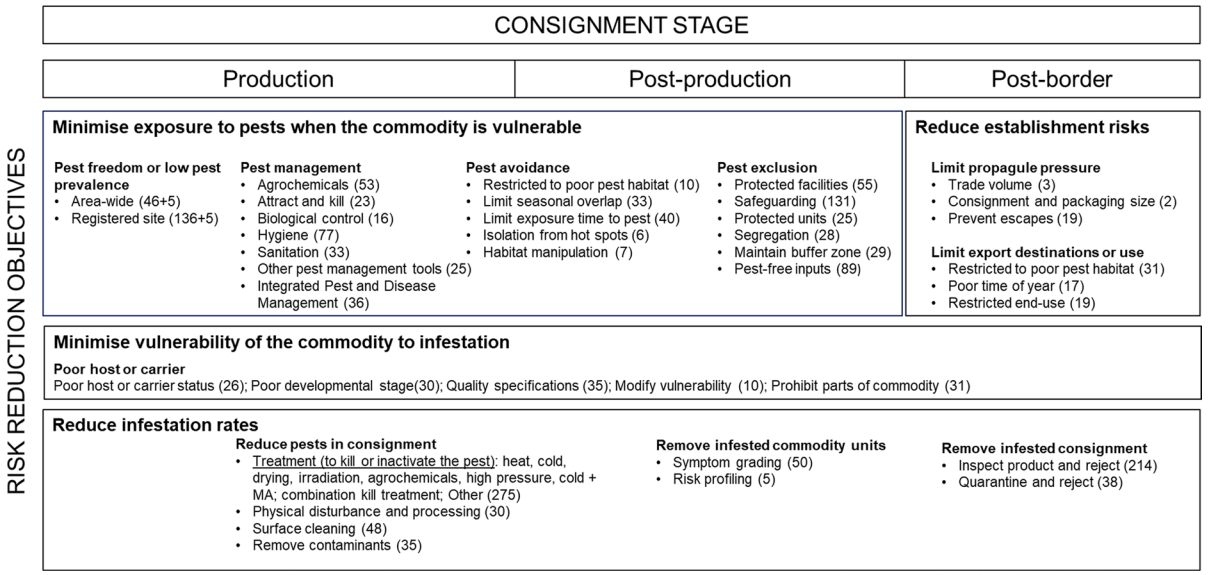

Fig. 1 Menu of measures, which groups measures into measure categories under each risk reduction objective, and identifies the consignment stages against which each risk reduction objective mostly applies. The number of times each measure was cited in the reviewed literature is given in brackets

- *Post-production*, which includes any storage, transport, handling and treatment from the point of harvest or manufacture through to departure from the regulated jurisdiction (country in the case of international trade).
- *Post-border*, which includes any storage, transport, handling, treatment and processing following departure from the regulated jurisdiction. This can include transit to the importing jurisdiction.

Here production and post-production relates to the regulated commodity. Therefore, the production stage for wood (timber) is pre-harvest (even though some processing may occur subsequently), but for wood packaging the production stage is when it is constructed.

The commodity can only become infested pre-border, so managing the risk of the commodity becoming infested by minimising exposure to the pest and vulnerability of the commodity only applies to production and post-production stages (Fig. 1). In contrast, establishment risks are reduced post-border, even though some measures such as consignment and packaging size may be instigated pre-border. Measures that reduce infestation rates in the consignment can be applied at any of the three consignment stages.

Description of measure categories

Categories of measures under each of the four risk reduction objectives are described in Table 1. Measure categories largely agree with those outlined in van Klinken et al. (2020). Pest freedom and low pest prevalence at site and area-wide scales were combined under a single measure category, as they reduce risk in a similar way. A broader range of measures that reduce establishment risk were identified under the current review, and this resulted in the original measure category "poor destination habitat" being subsumed under "limit export destinations or use", and the addition of a second measure category, "limit propagule pressure".

Risk objective: minimise exposure to pests when the commodity is vulnerable

A diverse range of measures that minimise exposure of the commodity to pests were identified (Fig. 1). All can be applied at the production stage and many can also be applied post-production, for example to prevent infestation by secondary or contaminating pests.

Measures that give confidence that the commodity is being produced or handled in areas that are

Table 1 Description of measure categories (Fig. 1), a brief explanation of evidence required to provide proof of efficacy, a qualitative assessment of how well-established methodologies are to support efficacy claims against the categories of measures and selected, and key references where required proof is discussed or applied

Risk reduction objective	Description of measure category	Evidence of efficacy		
Measure category		Required proof of efficacy [a]	Level of maturity	Key references
Minimise exposure				
Pest freedom or low pest prevalence	Pest monitoring to demonstrate that pests are either absent or below an acceptable threshold, within the registered site or production area. Exceeding the threshold triggers either a corrective action or suspension of the registered site or area.	Evidence that surveillance gives sufficient confidence in pest freedom, or that infestation rates in the commodity will be acceptably low provided the detection threshold is not exceeded. This is influenced by efficiency of the surveillance method, surveillance design and pest biology. Efficacy of corrective actions needs to be demonstrated.	Variable	IAEA (2011); ISPM22, IPPC Secretariat (2016c); ISPM10, IPPC Secretariat (2016d); ISPM29, IPPC Secretariat (2017e); ISPM4, IPPC Secretariat (2017f); ISPM26, IPPC Secretariat (2018b); ISPM30, IPPC Secretariat (2019a); Jang et al. (2014); Lance (2014)
Pest management	A wide range of pest management options can be used singly or in combination to minimise pest populations when susceptible hosts or carriers are present.	Evidence to set management objectives (e.g., pest abundance thresholds), and to show that pest management measures will achieve those.	Low	Cohen and Yuval (2000); Dent and Binks (2020); Dominiak (2019); Lloyd et al. (2010)
Pest avoidance	Minimising the overlap of vulnerable commodity stages with pests in space and time. Avoidance can be partial or complete.	Evidence (knowledge of biology, empirical data or modelling) to demonstrate that overlap between pest and susceptible stages is limited or absent.	Moderate	Araujo et al. (2019); Grechi et al. (2021); Hammons et al. (2010)
Pest exclusion	Partial or complete exclusion of the pest from the commodity, during production or post-production. Measures often combine physical barriers with management practices.	Demonstrate that physical barriers and management practices achieve sufficient pest exclusion.	Variable	Chouinard et al. (2016); Sauphanor et al. (2012); Xia et al. (2019)
Minimise vulnerability				
Poor host or carrier	Take actions that ensure that the traded commodity is a relatively poor host or carrier for the pest, at relevant pest abundances.	Determination of the relationship between pest exposure (pest abundance, duration, physiological status) and infestation rate for relevant developmental stages and qualities of the commodity. In some cases, pest survival and development in the commodity may also be important. Data on grading efficacy where relevant.	Low	Bellamy et al. (2013); Follett et al. (2021); ISPM37, IPPC Secretariat (2018a)

Table 1 (continued)

Risk reduction objective	Description of measure category	Evidence of efficacy		
Measure category		Required proof of efficacy [a]	Level of maturity	Key references
Reduce infestation rates				
Reduce pest in consignment	Infestation rates are reduced by either killing/inactivating the pest, removing pests from the commodity, or removing contaminants that are at risk of infestation. A wide range of methods are possible.	Needs to consider mortality, removal or inactivation rates of relevant life stages.	Established	Balagawi et al. (2021); Clarke (2019); Heather and Hallman (2008); ISPM42, IPPC Secretariat (2018c); ISPM18, IPPC Secretariat (2019c); ISPM43, IPPC Secretariat (2019g); ISPM28, IPPC Secretariat (2021c); Moirangthem and Baik (2021)
Remove infested commodity units	Removing commodity units that are or could be infested.	Determination that symptom grading or risk-profiling will reduce infestation rates in the consignment to acceptable levels.	Low	Gould (1995); Hattingh et al. (2020); Xia et al. (2021)
Remove infested consignment	Inspection of the commodity and rejection or redirection of the consignment, or suspension of the registered site or production system, if a pest threshold (typically zero) is exceeded.	Demonstration that detection efficacy and sampling regime will achieve the required sensitivity.	Variable	Cannon (1998); ISPM34, IPPC Secretariat (2016a)
Minimise establishment risk				
Limit propagule pressure	Limit the likelihood that sufficient pests, if they were present and alive in the traded commodity, will escape to establish.	Demonstrate the relationship between actions to limit propagule pressure with establishment likelihood, taking into account relevant supply chain, biological (e.g., Allee effects) and environmental factors.	Moderate	Baker et al. (2009); Mangan et al. (1997); Yamamura and Katsumata (1999)
Limit export destinations or use	Only allow consignments to be released at destinations where and when, or utilised in a way that, the pest is unlikely to establish.	Demonstrate that the risk of establishment is sufficiently low (pest biology, and environmental and seasonal conditions) if pests were to escape the consignment.	Established	Camac et al. (2020); ISPM11, IPPC Secretariat (2017d); MacLeod and Baker (2003); Neven et al. (2018)

[a] across the range of conditions and pest abundance level to which the commodity is exposed to, and confirmed under commercial conditions

either **pest-free or have low pest prevalence** could be applied either regionally (e.g., *pest free area* or *area of low pest prevalence*) or just to the *registered site*. Here registered site refers to production or post-production businesses that are registered for trade, which can include *pest free production sites* or *pest free places of production*. Threshold exceedance has consequences for all producers if applied regionally whereas it may only affect individual producers if applied at the registered site scale. The scale of application also has implications for how monitoring is designed, how corrective action and suspension thresholds are set and what corrective actions may be required.

A wide range of **pest management** options can be used singly or in combination to minimise exposure risks to pest populations when susceptible hosts or carriers are present. Measure options were expanded from those published in van Klinken et al. (2020) for fruit. Calendar and risk-based spraying were grouped into *agrochemicals* to reflect the wide range of ways chemicals can be applied. It is also consistent with the terminology used under measures for reducing infestation rates, reflecting the dual role agrochemicals can have in reducing risks. Field hygiene was expanded to *hygiene* as hygiene can be applied both during production and post-production to help manage pest populations. *Hygiene* referred to the management of alternative hosts, and removal of potential hosts, sources of inoculum or carriers (such as unharvested produce and dead leaves). It was distinguished from *sanitation* which we used to describe cleaning, washing or disinfecting equipment and facilities to manage pest abundance and transference risks, which is a common practice across the supply chain. *Attract and kill* was added to capture a range of techniques such as bait sprays, mass-trapping, sticky traps and pheromone lures, noting that these can also include agrochemicals to provide the kill function.

Pest avoidance is achieved by partially or completely preventing the overlap of a vulnerable commodity with pests in space and time. Measures proposed by van Klinken et al. (2020) remained unchanged: ensuring the commodity is produced or handled in areas where pest prevalence is limited by *poor habitat* or *limited seasonal overlap*, or by *limiting exposure time*. Additional measures identified through the review were limiting production or handling to areas away from identified "hot spots" such as towns (*isolation from hot spots*), and *habitat manipulation* to make it less suitable for the pest (e.g., through controlling lighting, temperature and humidity).

Partial or complete **pest exclusion** can be achieved at different scales. *Protected units* applies to, for example, fruit bagging or wrapping of machinery. *Safeguarding* was used to refer to pest physical pest exclusion (with associated management practices) when applied between the scale of individual units and protected facilities. It most often related to storage of produce, secure transport and secure packaging. Commodities can also be safeguarded from infestation as it passes through the supply chain by ensuring secure conditions during transportation or within non-secure facilities. This is a more restricted usage of the safeguarding term than that of Griffin (2012a) which included non-physical measures such as "shipping season asynchrony". *Protected facilities* includes protected cropping, and secure processing, treatment and storage facilities. *Segregation* can be used to ensure a regulated article does not mix in space or time with unregulated commodities or other potential pest sources. Typically, these pest exclusion measures combine physical infrastructure with management practices, e.g., to maintain the integrity of processing facilities. New measures, *maintaining buffer zones* and *pest free inputs*, generally relate to management activities that contribute to pest exclusion or to the maintenance of pest free areas.

Risk objective: minimise vulnerability of the commodity to infestation

Measures can minimise the vulnerability of the traded commodity, and therefore infestation risk, at relevant pest abundances. This can be achieved by limiting trade to commodities (*poor host or carrier status*), or to stages (*poor developmental stage*) or quality (*quality specifications*) of commodities, that are poor hosts or carriers. *Quality grading* was renamed to *quality specifications* and moved from reducing infestation rates as it reduces risk by setting requirements on the quality of commodity that can be traded. A new measure, *modifying vulnerability*, was added for situations where the physical or chemical properties of the commodity is altered to make it less vulnerable. For example, kiln drying timber may make it less susceptible to insect attack (ISPM31, IPPC Secretariat

2016b). *Removing or prohibiting parts of the host or carrier* that are most vulnerable to infestation (e.g., removing bark from timber and bare-rooting plants; Leal (2010)) was also added.

Risk objective: reduce infestation rates

Reducing infestation rates (assuming that there was a risk of infestation) can be achieved at the consignment level by measures that **reduce pests in the consignment, remove infested commodity units**, or at the pathway level by measures that prevent the movement of infested consignments if infested commodity is found through inspection (**remove infested consignment**, previously referred to as "Inspect and reject"). Many of these measures can be applied at multiple consignment stages. Measures previously identified for horticulture (van Klinken et al. 2020) remained largely unchanged. *Kill treatments* were pooled, reflecting the diverse range of chemical and physical options that are possible across different commodities. *Physical disturbance and processing* was added as a distinct measure as it often relates to production processes (e.g., processing can be added as a post-border requirement), although physical disturbance can also be a specified kill treatment. Measures for removing the pest from the commodity was expanded from *surface cleaning* to include *removing contaminants*. **Removal of infested commodity units** can be achieved through *symptom grading* or *risk-profiling*. The latter is a new measure where risk traits rather than pest symptoms are used to identify units (e.g., shipping containers) that are most likely to be infested, and where the consequence of detection is removal of the unit rather than the "consignment". Measures that **Remove infested consignments** can be applied during production (e.g., crop inspection) through to post-border. A *Quarantine and reject* measure was included as it is commonly used for living plants, with quarantining being used to improve the detection likelihood of cryptic pests such as plant diseases (USDA 2002).

Risk objective: reduce establishment risks

If a pest enters or introduces are jurisdiction with a commodity then PRA is concerned with the likelihood of establishment, spread and economic loss (Devorshak 2012). Risk management measures that we found primarily relate to reducing establishment risks. The only such measure identified in the review of systems approach protocols was ensuring that consignments were imported to poor habitat (van Klinken et al. 2020). Our review identified a much broader range of measures which we grouped according to whether they reduce establishment risk through **limiting propagule pressure** or by **limiting export destinations or use** (Fig. 1).

Measures that **limit propagule pressure** minimise the likelihood that sufficient pests will escape from consignments, often enough, for establishment to occur. *Restricting trade volume* limits the number of pests that could be released through time, whereas *limiting consignment size* (or how the commodity is packed within the consignment) can limit the number of pests that may be released at any one time or place. These restrictions and limits contribute to reducing the number of individuals that could arrive simultaneously, meaning that stochastic population processes and Allee effects are more likely to prevent establishment (Drake and Lodge 2006; Leung et al. 2012). Measures to p*revent pests escaping* from the consignment are similar to pest exclusion measures, but are focussed on inclusion rather than exclusion. We only included it as a distinct measure when it was associated with other requirements such as transport to post-border processing or treatment facilities.

Export destinations and use can be limited spatially (*restricted to poor habitat*) or seasonally (*poor time of year*) to areas where establishment risks are expected to be low, as determined by environmental conditions, host availability and other factors. Pests on commodities that cross hemispheres are frequently exposed to counter-seasonal conditions that may reduce the risk of establishment (Eschen et al. 2015a). *End-use can also be restricted* (e.g., wood chips for biofuel only, ISPM41, IPPC Secretariat (2019e)) at the destination to limit establishment likelihood. This was differentiated from post-border processing requirements that were included under measures that reduce infestation rates.

Inconsistencies in published measures, and how they were resolved

Some published measures were what we refer to as "measure elements", where the action on its own is insufficient to reduce risk. For example,

"surveillance", "sampling", "testing" and "monitoring" would reduce risk only if a threshold is set, and a consequence of threshold exceedance is defined (Table 1). Where sufficient context was provided we assigned these to measures, such as *inspect product and reject*, *pest freedom or low pest prevalence* or *integrated pest and disease management* (n = 76). For a small number of the measures cited in the literature (n = 35; < 2%), insufficient information was provided to assign them to a risk reduction objective, measure category or measure type. This was generally because it was difficult to interpret how the suggested measure would reduce risk without additional context. For example, "harvest technique and handling" (ISPM13, IPPC Secretariat 2021a) or "silviculture practices" (ISPM41, IPPC Secretariat 2019e). The European Food Safety Authority listed eight "supporting measures", defined as measures that do not directly affect pest abundance (EFSA PLH Panel et al. 2018) which we classified as either administrative (e.g., certification) or measure elements (e.g., surveillance, testing and laboratory testing).

Evidence of efficacy

We found an extensive literature on how efficacy of measures can be established. This included internationally agreed "guidelines", reviews and focussed studies. However, the strength of the literature was variable, depending on the category of measures (Table 1). Requirements for demonstrating efficacy were best established for measures that kill, inactivate or remove pests from the commodity, reflecting the widespread use of "end point treatments" (ISPM28, IPPC Secretariat 2021c).

Minimise exposure to pests

Measures that reduce exposure of commodities to pests are diverse and are often used in combination. There is a rich literature on providing confidence in *pest free areas* or *area-wide low pest prevalence*, however, this typically does not extend to providing confidence in situations where monitoring is restricted to the registered site (Cohen and Yuval 2000; Grechi et al. 2021). Methods to support the establishment of pest abundance thresholds are also not well supported. There is an extensive literature on *pest management*, including detailed reviews, modelling and empirical studies (Dent and Binks 2020). However, this literature almost exclusively focusses on minimising production losses or maintaining quality standards through, for example, the maintenance of economic injury levels (Dent and Binks 2020; Peterson et al. 2018). Establishing the relationship between pest management and the risk of pest movement through trade is a related question, but typically requires stringent maintenance of much lower pest thresholds. We found no standard approaches for this, although empirical studies have quantified the relationship between the efficacy of pest management and pest densities for some quarantine pests (Cohen and Yuval 2000; Sauphanor et al. 2012). Bioclimatic modelling and empirical studies can be used to support *pest avoidance* measures, such as demonstrating that production occurs in poor pest habitat (Neven et al. 2018) and demonstrating limited seasonal overlap (Araujo et al. 2019; Hammons et al. 2010). Studies on *pest exclusion* measures are limited, although there are well-established standards for secure packaging (safeguarding).

Minimise vulnerability of commodity to infestation

International standards have been developed to establish host status for some pests. For example, methodologies have been developed for fruit flies to assess whether a commodity is a natural host, conditional host (can only support the pest in semi-natural conditions) or non-host (ISPM37, IPPC Secretariat 2018a). Relative host vulnerability has also been established using often high pest abundance under laboratory or semi-natural conditions (e.g., Bellamy et al. (2013); Follett et al. (2021)). However, development status or quality is rarely explicitly considered when assessing relative vulnerability of a host or a carrier, though it can have a significant effect (Tonina et al. 2020). Physiological status of the pest, as influenced by environmental conditions, time of year, developmental host, and the availability of alternative hosts, can also have a significant effect on infestation rates (Merkel et al. 2019; Papadopoulos et al. 2001). These factors all contribute to making it difficult to relate relative host or carrier vulnerability assessments generated under artificial conditions to what might happen under environmental conditions and the typically low pest abundance encountered under commercial settings. We found no examples where methods have

been developed or applied to take these considerations into account, although theory and methodologies could potentially be drawn from other disciplines such as weed biological control (Sheppard et al. 2005).

Reducing infestation rates

Considerable effort has gone into developing internationally agreed methodologies for many of the typical end point treatments such as cold, fumigation and irradiation (ISPM28, IPPC Secretariat 2021c). In contrast, we found limited literature demonstrating the efficacy of symptom grading or risk-profiling (Bragard et al. 2021; Xia et al. 2021). Inspection and rejection measures are almost universally required, and calculation of their efficacy is described in ISPM31, (IPPC Secretariat 2016b). Yamamura and Katsumata (1999) developed a framework that incorporates biological attributes of the pest in combination with disinfestation treatments and export sampling protocols to examine the probability of introduction. However, we found few examples where key parameters such as the probability that inspection of an infested unit will detect a pest (Gould 1995; Xia et al. 2021). Most studies have focussed on post-production inspections. We found no examples where the supporting science has been extended to quantify inspection sensitivity conducted during production (e.g., crop inspections) or to sampling of high-risk fractions (e.g., discarded produce that are more likely to be infested).

Establishment risk

Measures identified in this study that reduce establishment risk are not widely used (Fig. 1). Nonetheless, there is a large ecological (Drake and Lodge 2006; Liebhold et al. 2016) and biosecurity (Bartell and Nair 2004; Jamieson et al. 2021; Ormsby 2022; Turner et al. 2020) literature on methods to estimate establishment risk. These can inform pest risk assessments (ISPM 11, IPPC Secretariat 2017d; MacLeod and Baker 2003), and support the development of measures that reduce establishment risks. Establishment risk is determined by propagule pressure (number and timing of escaping pests), suitability of the destination for establishment, and the biology and physiological status of the pest (e.g., life stage, reproductive rates, reproductive mode, Allee effects, stochasticity and ability to survive adverse conditions) (Bartell and Nair 2004; Saccaggi et al. 2016). The suitability of habitat, or the invasibility of the recipient ecosystem, can be driven by both abiotic and biological factors, and there is a wide range of methods for predicting habitat suitability (e.g., Camac et al. 2020; Neven et al. 2018). The physiological status of the pest on arrival is less often considered, but can have a significant effect on establishment risk, for example where the commodity crosses hemispheres (Eschen et al. 2015a). The Maximum Pest Limits (MPL) concept (Baker et al. 1990) reflects the maximum number of pest individuals permissible in consignments during a specified time and to a specified location (Baker et al. 1990; Jamieson et al. 2013). MPL is therefore related to propagule pressure and varies considerably between pests (Baker et al. 1990; Ormsby 2022). Several studies have extended and applied the MPL methodologies to different pests and commodities (e.g., Cannon 1998; Mangan et al. 1997; Vail et al. 1993), most recently to pests of wood packaging (Ormsby 2022), however a more comprehensive methodology for assessing the efficacy of specific measures aimed at reducing establishment risk (Fig. 1) is lacking.

Usage of measures in the literature

Of the 39 measure types we identified, the most commonly encountered ones were *kill treatments*, *inspect product and reject*, *pest freedom or low pest prevalence at the registered site level* and *safeguarding* (Fig. 1). Some measures such as removal of infested commodity units through *risk profiling*, and *trade volumes* and *consignment and packaging size* to limit propagule pressure, were rarely encountered.

Several literature sources identified most measure types (Table 2). ISPMs together were the most comprehensive, but did not include the three measures reducing establishment risk by limiting propagule pressure (*trade volume*, *consignment and packaging size*, and *prevent escapes*), *quality specifications* (minimise vulnerability) and *risk profiling* (remove infested commodity units). Only nine measures were not already being used in publicly available systems approach protocols for horticultural products, as listed in van Klinken et al. (2020). Similarly, 30 of the 39 measures were included in a report on managing plant pathogen trade risks (USDA 2002). "Risk Reduction

Options that embrace all types of phytosanitary measures that could be implemented for acting on a pest injurious to plants" listed by the European Food Safety Authority (EFSA PLH Panel et al. 2018) only identified 22 measures (Table 1).

Cited measures were mostly directed at minimising exposure to pests (49.6%) and reducing infestation rates (39.9%) (Table 2). Measures to minimise host or carrier vulnerability and reduce establishment risks were included in most of the main publications, although they were infrequently mentioned.

Usage of measures by commodity class

A diverse range of commodity classes can carry biosecurity threats (Table 3). Most can both be hosts and carriers of pests whereas vehicles, machinery and equipment (VME) and shipping are exclusively carriers. Commodity classes differ as to where in the supply chain infestation risk is greatest (Table 3). For living plants or plant products it is mostly during the production phase, although some pests are capable of infesting those products after harvest, are post-harvest specialists (e.g., many grain pests) or can be contaminants. For already manufactured products such as VME, wood packaging and some types of planting media, infestation risk will mainly or exclusively be post-production.

The number of references we found listing measures varied with commodity class, as did the number of measure types and the total number of times measures were cited (Table 3). Horticultural products have received the most focussed attention as judged by the number of times measures were cited, followed by plants for planting, and wood and wood products. This result likely reflects at least in part the state of the literature, with few citations found that review how trade-related biosecurity risks are managed for many of the commodity classes (Table 3).

Thirty-five of the 39 measures have been used or proposed for fruit and vegetables (Table 3). Missing were two measures for reducing infestation rates, *risk profiling* and *quarantine and reject*, and two of the six measures for reducing establishment risk, *trade volume* and *consignment and packaging size*. In fact, measures to reduce establishment risks were rare or absent for most commodity classes. Overall, eight of the 14 commodity classes listed less than half of the of the 39 measures. The *kill treatment* measure was identified for 13 of the 14 commodity classes, only being missed for plants in vitro. Other widely applied measures were *safeguarding* (12), *inspect product and reject* (11), *pest-free inputs* (10), *area-wide sites* that are pest free or low pest prevalence (9), *protected facilities* (9), and *hygiene* (8).

Discussion

In this paper we revise the previously published risk framework and menu of measures developed for horticulture (van Klinken et al. 2020) with the aim of making it applicable to all commodities, and to both pest risk assessment and pest risk management. We reviewed how measures have been used or suggested for use across relevant commodity classes, and what is required to demonstrate efficacy in reducing risk. The previously published risk framework, which outlined four risk reduction objectives and three production stages (van Klinken et al. 2020), required updating to be relevant to all commodities, and to incorporate additional measures. The main change to the risk framework was to adjust the terms applied to the three consignment stages to be relevant to any commodity class. The two pre-border stages, production and post-production, reflect very different infestation risk profiles within and between commodity classes. For example, the greatest infestation risks for fresh produce are typically during production (pre-harvest), whilst the post-production stage is most relevant for manufactured commodity classes such as VME (vehicles, machinery and equipment) and wood packaging, conveyances and shipping containers. It can also be most important for stored grain. The post-border stage is when the commodity can no longer become infested and when measures that reduce establishment risk in the event that infested commodities were to arrive take effect. Measures to reduce infestation rate can still be applied post-border. Measures were used in similar ways across commodity classes, but some appeared underutilised. This, combined with our observation that guidance was lacking on how to demonstrate efficacy of many measure categories, suggests that there is considerable opportunity for innovation in how risks are managed.

Harmonisation of risk terminology assists in communication, and the ease and usefulness of risk analyses (EFSA PLH Panel et al. 2018). By classifying

Table 2 The total number of measure types identified (from a total of 39 listed in Fig. 1), and times measures were cited (in brackets), in each reviewed publication, grouped by risk reduction objective. Sources are listed in order of decreasing number of listed measure types

References	No. of measure types (number of measures cited)				
	Risk reduction objective				
	Minimise exposure ($n=20$)[a]	Minimise vulnerability ($n=5$)	Reduce infestation rate ($n=8$)	Reduce establishment risk ($n=6$)	Total ($n=39$)
ISPMs (combined)[b]	20 (140)	4 (17)	7 (86)	3 (8)	34 (251)
Aust. Gov.(combined)[c]	16 (67)	4 (9)	8 (58)	4 (5)	32 (139)
RSPMs (combined)[d]	17 (73)	5 (10)	6 (46)	4 (8)	32 (137)
Yoe et al. (2020)	15 (31)	4 (5)	7 (45)	5 (13)	31 (94)
van Klinken et al. (2020)	17 (252)	4 (30)	6 (142)	3 (9)	30 (433)
USDA (2002)	15 (71)	4 (7)	7 (40)	4 (11)	30 (129)
MPIs (combined)[e]	13 (79)	4 (9)	7 (95)	2 (7)	26 (190)
Griffin (2012aa), (b)	12 (16)	3 (5)	5 (19)	4 (4)	24 (44)
IAEA (2011)	14 (21)	2 (2)	4 (9)	2 (2)	22 (34)
EFSA PLH Panel et al. (2018)	12 (17)	3 (3)	4 (9)	3 (3)	22 (32)
Quinlan et al. (2016)	11 (44)	2 (6)	4 (17)	–	17 (67)
Eschen et al. (2015b)	7 (7)	3 (5)	4 (8)	3 (3)	17 (23)
Dominiak (2019)	12 (21)	2 (3)	2 (7)	–	16 (31)
Meibusch et al. (2019)	6 (8)	2 (2)	5 (17)	2 (10)	15 (37)
Leal (2010)	7 (13)	3 (5)	3 (8)	1 (2)	14 (28)
Allen et al. (2017)	6 (9)	2 (4)	2 (13)	–	10 (26)
Clarke (2019)	4 (7)	2 (2)	2 (6)	1 (1)	9 (16)
All other references[f]	11 (27)	4 (8)	7 (70)	3 (5)	25 (110)
Total	*20 (903)*	*5 (132)*	*8 (695)*	*6 (91)*	*39 (1,821)*

[a] no. of measure types listed in Fig. 1

[b] ISPM references pooled together including – (IPPC Secretariat 2016a, b, c, d, 2017b, c, f, g, 2018b, c, d, 2019b, c, d, e, f, g, 2021b, d)

[c] Australian Government departments references pooled together including – (Australian Government 2019a, b, 2021a, b, c, 2022a, b, c, d)

[d] RSPM references pooled together including – (North American Plant Protection Organization (NAPPO) 2009, 2011, 2012, 2013, 2017, 2018)

[e] MPI references pooled together including – (Ministry for Primary Industries (MPI) 2018, 2020, 2021a, b, c, d, e, f, g, h, i, j)

[f] 14 references pooled together including – (Balagawi et al. 2021; Clarke 2004; Follett and Neven 2006; Government of Canada 2014; Grousset et al. 2020; Hattingh et al. 2020; Heather and Hallman 2008; Holt et al. 2018; IPPC Secretariat 2020; Marchioro and Faccoli 2021; Maxwell et al. 2014; Moirangthem and Baik 2021; United Nations Conference on Trade and Development 2019; WHO 2021)

on how they reduce risk we identified 39 unique measures, grouped under ten categories and four risk reduction objectives. This greatly simplifies the diversity of measures described in the literature, and extends the options provided in existing lists. Most of the 39 measures reduced risk by minimising exposure to pests (20 measures under four measure categories) or reducing infestation rates (8 measures under 3 measure categories). These measures were also the most widely encountered overall, and were well

Table 3 For each commodity class: the consignment stage at which infestation risk is greatest; the measures identified in the literature survey to manage that risk, grouped by risk reduction objective; and the total and most important references citing measures

Commodity[a] class	Infestation risk		No. of measure types (and times cited)					No. of references citing measures[c]	Key references
	Consignment stage		Risk Reduction Objective (total measures, Fig 1)				Total		
	Production	Post-production	Minimise exposure ($n = 20$)[b]	Minimise vulnerability ($n = 5$)	Reduce infestation rate ($n = 8$)	Reduce establishment risk ($n = 6$)	($n = 39$)		
General	Yes	Main	18 (65)	4 (14)	8 (92)	5 (19)	35 (190)	18	ISPM14, IPPC Secretariat (2017g)
Plants and plant products			17 (102)	4 (17)	7 (82)	5 (21)	33 (222)	4	USDA (2002)
Fruit/vegetables	Main	Yes	20 (408)	5 (49)	6 (207)	4 (14)	35 (678)	14	ISPM14, IPPC Secretariat (2017g); van Klinken et al. (2020)
Plants for planting	Main	Yes	17 (81)	4 (10)	5 (55)	4 (5)	30 (151)	11	ISPM36, IPPC Secretariat (2019d)
Plants in vitro	Main	Yes	9 (28)	2 (3)	3 (15)	1 (2)	15 (48)	6	MPI (2021b, c, f, h)
Growing medium	Yes	Yes	5 (10)	1 (1)	5 (15)	1 (1)	12 (27)	3	ISPM40, IPPC Secretariat (2017b)
Cut flowers and branches	Main	Yes	15 (46)	3 (4)	4 (21)	1 (1)	23 (72)	4	Quinlan et al. (2016) Australian Government (2019b)
Grain	Yes	Main	6 (8)	2 (2)	5 (26)	2 (10)	15 (46)	3	Meibusch et al. (2019)
Seeds for planting	Main	Yes	11 (29)	3 (3)	6 (31)	2 (2)	22 (65)	4	ISPM38, IPPC Secretariat (2021b)
Bulbs/tubers/seed potatoes	Main	Yes	9 (25)	3 (4)	6 (22)	3 (4)	21 (55)	3	RSPM3, NPPO (2011b)
Processed plant products	No	Yes	7 (10)	-	4 (18)	1 (3)	12 (31)	2	MPI (2021e, g)

Table 3 (continued)

Commodity[a] class	Infestation risk		No. of measure types (and times cited)					No. of references citing measures[c]	Key references
	Consignment stage		Risk Reduction Objective (total measures, Fig 1)				Total		
	Production	Post-production	Minimise exposure ($n = 20$)[b]	Minimise vulnerability ($n = 5$)	Reduce infestation rate ($n = 8$)	Reduce establishment risk ($n = 6$)	($n = 39$)		
Conveyance	No	Yes	6 (6)	-	4 (12)	–	10 (18)	3	RSPM33, NPPO (2011b)
Shipping containers	NA	yes	11 (23)	–	5 (16)	1 (1)	17 (40)	7	IPPC Secretariat (2020) MPI (2020)
Vehicles Machinery and Equipment (VME)	No	Main	8 (16)	1 (1)	4 (22)	–	13 (39)	3	ISPM41, IPPC Secretariat (2019e) Australian Government (2022a)
Wood, wood products	Yes	Main	12 (46)	5 (23)	4 (58)	4 (8)	25 (135)	7	RSPM 41, IPPC Secretariat (2019e) Leal (2010)
Wood packaging	Main	Yes	–	1 (1)	1 (3)	–	2 (4)	1	ISPM 15, IPPC Secretariat (2021d)
Total			*20 (903)*	*5 (132)*	*8 (695)*	*6 (91)*	*39 (1,821)*	*93*	

[a] Here used in the broad sense to include any traded article

[b] no. of measure types listed in Fig. 1

[c] ISPMs are included as a single citation

represented across the diverse commodity classes. Minimising exposure to pests is widely recognised as being an important contributor to managing biosecurity risk or as a stand-alone requirement (e.g., pest free areas), whereas measures that reduce infestation risk are commonly used as single point treatments. Measures to minimise vulnerability of the commodity were only applicable to commodities for which there is variability in vulnerability, for example with age, stage of development or quality condition, or where vulnerability can be modified. Measures that reduce establishment risk should infested consignments happen to arrive onshore were poorly represented across all commodities, although options that either limit commodity destination or use, or limit propagule pressure, were identified. Lack of attention for measures aimed at reducing establishment risk may reflect a focus by regulators on infestation risks rather than establishment likelihoods (Baker et al. 1990; Jamieson et al. 2013), despite establishment likelihood and potential impact being an explicit focus of pest risk assessments (ISPM11, IPPC Secretariat 2017d; Jamieson et al. 2021).

The risk framework and menu of measures provides options for designing and revising protocols so that they meet the requirement of being effective, whilst remaining least trade restrictive (World Trade Organization 1994). Often only a single measure is

required for trade: pest free areas rely on monitoring with suspension of all participating registered sites if a detection threshold is exceeded; conditional non-host protocols rely on poor host or carrier status or poor developmental stage; single point treatments or a single kill treatment (IAEA 2011); and some protocols rely on only permitting distribution of the commodity into areas where establishment risks are low. Nonetheless, additional supporting measures may also be required. For example, pest freedom protocols may also require pest management measures (e.g., hygiene), pest avoidance measures (e.g., if pest free areas can only be applied in areas isolated from incursions) and pest exclusion methods (such as maintaining buffer zones and ensuring pest free inputs) (ISPM4, 26, IPPC Secretariat 2017f, 2018b). These measures all address a single risk reduction objective and as such can be considered "dependent" (IAEA 2011). In contrast, phytosanitary systems approaches combine measures from multiple risk reduction objectives (van Klinken et al. 2020). For example, a kill treatment may also require measures to minimise exposure to the pest (IAEA 2011). The menu of measures allows potential measures to be identified, and decisions made regarding which combination will provide an Appropriate Level of Protection (ALOP) (Griffin and Neely 2012) whilst also being least trade restrictive. It can also help identify commercial measures that are already contributing to risk reduction, and guide decisions as to which measures need to be regulated.

A critical element of risk-based trade is providing evidence that measures are effective in reducing risk (Devorshak 2012; FAO 2016; Follett and Neven 2006). We found considerable variation within and across categories of measures in the level of guidance and agreement as to what is required to demonstrate efficacy. Methodologies were most established for demonstrating pest freedom, killing pests in commodities, and removing pests from the commodity. More work is needed to provide guidance for many of the other measures. For example, although principles have been developed to demonstrate area-wide pest freedom (Lloyd et al. 2010; Vreysen et al. 2007), little has been done on how to establish corrective action or suspension thresholds to support low pest prevalence measures, re-instate pest free areas following an incursion (but see Ormsby 2021 for a recent approach for fruit flies), or design site-based monitoring (Guimapi et al. 2020). A substantial literature relates pest management activities to managing production losses, but we found little guidance on how to directly quantify the contribution of pest management to reducing the risk of pest movement through trade. Application of quality specifications through quality grading is commonly recognised as being an important commercial practice that reduces biosecurity risks of fruit (Hattingh et al. 2020), but we found few studies quantifying its benefits. This may contribute to quality specifications rarely being explicitly included in trade protocols. The Maximum Pest Limit concept (Baker et al. 1990; Yamamura and Katsumata 1999; Ormsby 2022), provides a mechanism for quantifying the efficacy of measures that reduce establishment risk. However, actual quantification of measures that can reduce establishment risk, such as limiting trade volume, consignment and packaging size and export destinations or use, has received little attention.

The vulnerability of hosts or carriers to becoming infested is a key aspect to establishing risk (e.g., Vail et al. 1993). It also underpins measures that relate to limiting protocols to less vulnerable types, developmental stages or quality specifications of commodity. However, we found methodologies for demonstrating the efficacy of such measures to be poorly developed, beyond simply supporting conditional non-host claims (ISPM37, IPPC Secretariat 2018a). A recent attempt at developing a standard Host Suitability Index (HSI) for fruit flies (Follett et al. 2021) is a step, but it does not explicitly consider the relationship between host quality and host vulnerability, or pest abundance and infestation rate, two important aspects affecting infestation rate and the efficacy of measures aimed at addressing risk of infestation. There has, nonetheless, been considerable basic research on host-pest/pathogen relationships, as well as applied research in biological control for example (Sheppard et al. 2005) which could inform the development of a more robust methodology.

Conclusion

Globalisation and trade pose substantial biosecurity risks. A key challenge for biosecurity practitioners and policy makers is to apply risk-based principles to identify where and when risks need to be managed,

and to ensure that the strength of any required measures are proportional to risk (Griffin and Neely 2012). Here we have generated a menu of measures, with measures classified according to how they reduce risk. This expands on an earlier version through review and analysis, making it applicable to a much broader range of plant pests and commodity classes. Variation in the extent to which measures are used within and across different commodity classes suggests there is considerable potential for innovation in terms of which measures are applied and in what combination. However, many measures are still lacking clear guidelines on how to demonstrate efficacy. Classification of measures according to how they reduce risk, and further work to provide clear guidelines on how efficacy of each type of measure can be demonstrated, will provide a robust basis for the continued development, refinement and communication of efforts to both assess and manage the risk of global, trade-related pest movement.

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Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

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