

Plant Pest Impact Metric System (PPIMS): framework and guidelines for a common set of metrics to classify and prioritise plant pests

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Abstract

Agricultural stakeholders need a common set of metrics to evaluate plant pest impacts to facilitate transparency and harmonisation of pest management and prioritisation across spatial scales and jurisdictions. We propose a classification system that articulates, defines and classifies the magnitude of impacts (historical, current or potential) of pest species (alien and native) in plant production systems. Metrics were identified and criteria defined through consideration of economic parameters, risk assessment standards and guidance tools, discussions with pest risk assessment practitioners and recent advances in environmental impact classification schemes. Twenty metrics were identified and assigned to one of four key metric types: spatiotemporal, market-driven, primary response and mid- to long-term response. *Host crop value*, *Market access*, *Feasibility of management* and *Reversibility* were identified as disruptor metrics, likely to influence overall classification by at least twice that of other metrics. Application of the system found it was able to classify well-known pests by importance, capturing changes in impact status as the management programme progressed for one pest, and how it was influenced by the geographic scale of assessment for another. Our work demonstrates the value of integrating plant protection science with invasion biology to derive a comprehensive measure of pest impact in agroecosystems that can be utilised by all plant biosecurity stakeholders.

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Introduction

Plant pests can seriously affect food security, trade and farming practices and profitability (Charles and Dukes 2007; Dobson *et al.* 2013; Oerke 2006). Here, we expand on the definition of plant pests outlined by the International Plant Pest Convention (FAO 2016c), to define plant pests as any organism, such as pathogens, insects or invasive plants, that can directly or indirectly limit plant productivity and production values through their presence (FAO 2016c). They affect a wide range of stakeholders with vested and varied interests in plant protection and associated resource investment, including farmers, industry bodies and policy-makers. Pest impacts are often referred to as effects and consequences, depending on the disciplinary background of the stakeholder and the nature and history of associated policy and/or management applications (Falk-Petersen *et al.* 2006; Jeschke *et al.* 2014). While the impacts of plant pests are often characterised as significant and dramatic (as the most damaging and obvious pests capture most attention, and may therefore be the most important to control), they vary considerably in both their nature (environmental, economic and socio-political) (Charles and Dukes 2007; Dobson *et al.* 2013) and magnitude (e.g. minimal to massive, *sensu* Blackburn *et al.* (2014)). Magnitudes of pest impacts vary according to the species in question (Blackburn *et al.* 2014), prevailing spatiotemporal dynamics (Leung *et al.* 2012), the vulnerability and response of the recipient ecosystem, host plant or crop (Blackburn *et al.* 2014), and the management response of the affected industry or departmental authority (Zadoks and Schein 1979). Despite a large body of research studying the effects and damage caused by pest species, the extent and nature of their impacts are often poorly explored, and rarely discussed in a general framework (Blackburn *et al.* 2014; Jeschke *et al.* 2014; Parker *et al.* 1999).

Classification of pest impacts has important and intersecting applications, from the localised scale of the farm gate to the generalised global arena of plant biosecurity. At local scales, considerable efforts have been made to define crop loss assessment, yield losses, economic injury levels and damage thresholds for plant production systems, often within an integrated pest management (IPM) context, in order to boost productivity and improve crop protection and management outcomes (Oerke 2006; Savary *et al.* 2006). Meanwhile, at the generalised scale, many qualitative and quasi-quantitative classification systems have been developed by a range of jurisdictions (local governments, to nations and global regions) for pest risk assessment and prioritisation purposes, to allocate resources most effectively and better protect plant industries (e.g. UK: Baker *et al.* 2014; and Europe: Brunel *et al.* 2010; EPPO 2011; Griessinger *et al.* 2012). However, at all scales, calls to collect substantive data to inform generalised classifications (i.e. by quantifying and describing yield loss due to a wide range of pests across space and time), have consistently remained unheeded (Savary *et al.* 2006). This limits our ability to objectively compare and predict plant pest impacts.

Attempts to clarify and describe pest impacts, particularly for biosecurity purposes, often fail to clearly define an overall and/or measurable method of classification (see Hill (1987) and Falk-Petersen *et al.* (2006)). Terminology such as “low, medium, high” (McDonald *et al.* 2015), “minor, moderate, major” (EPPO 2011), “indiscernible, significant” (Australian Department of Agriculture and Water Resources 2016), or “major, massive” (Baker *et al.* 2014), along with vague qualifying statements such as “unlikely to be noticeable” (Australian Department of Agriculture and Water Resources 2016), provide little clarity and can lead to multiple and potentially conflicting interpretations (see MacLeod and Pietravalle 2017, and references therein). Even when some measurable and quantitative terms are alluded to (e.g.

EPPO 2011; McDonald *et al.* 2015), they either fail to provide standardised guidelines and numerical/quantitative ranges or use classes and interval ranges which are difficult to understand outside of their specific context, such as using dollar values rather than proportions of national GDP or industry value(s), undermining any meaningful comparison. Clear articulation of a standardised conceptual methodology capable of robust comparison and risk communication over time and space would be a valuable contribution to the field of pest risk and impact assessment.

Many conceptual frameworks for defining and classifying pest impacts have been developed in the invasion biology literature, chiefly focusing on qualitative assessments of the environmental impacts of invasive alien species (Kumschick *et al.* 2015b). One of the most notable of these frameworks, by Blackburn *et al.* (2014), is a standardised, largely qualitative method of classification, that assigns species to their highest recorded level of deleterious environmental impact. This framework is known as the Environmental Impact Classification for Alien Taxa (EICAT) (Hawkins *et al.* 2015). EICAT is notable as it has been adopted by the IUCN (International Union for Conservation of Nature) as a standard methodology to classify the impacts and prioritise the management of a wide array of invasive alien species, in order to meet both Aichi Target 9 of the Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity (CBD) and Target 15.8 of the Sustainable Development Goals (SDGs) commitments (IUCN 2016). However, its adoption to assess agricultural pest impacts is limited by a lack of criteria for socio-economic and trade impacts, which are largely prevalent in plant production systems. A recent complementary framework developed by Bacher *et al.* (2018), the Socio-Economic Impact Classification of Alien Taxa (SEICAT), partly addresses this gap by exploring the magnitude of invasive species impacts on human well-being, based on the capability approach from welfare economics (effectively a measure of the change in human activity as a common metric for evaluating impacts on well-being, at similar scales to that of the EICAT framework). Similarly, Ojaveer *et al.* (2015) partly addressed the lack of criteria for socio-economic and trade impacts by exploring the protection of environmental, economic, socio-cultural and human health “value sets”. However, Ojaveer *et al.* (2015) focused exclusively on the marine system. Unfortunately, both the Bacher *et al.* (2018) and Ojaveer *et al.* (2015) frameworks have limited emphasis on trade or market impacts and notably, neither framework attempted to provide a tangible set of *measurable* impact metrics, or address impacts on plant production.

Current plant industry related impact assessments are often limited to specific taxa and cover all stages of invasion (i.e. from transport and establishment to increase in abundance, spread and impact), with no explicit focus on impact (see Leung *et al.* (2012) for a comprehensive review). At the very least, semi-quantitative metrics or scalar metrics should be developed that are, (1) simple enough to apply across a range of pest taxa, cropping systems and spatiotemporal scales, and, (2) complex enough to provide a measure of impact, while avoiding, or at least recognising, double-counting (i.e. accounting for the same type of impact twice – perhaps by having two very similar and/or interacting metrics within any given impact metric system).

Here, we propose a standardised, metricised and universal framework for quantifying and comparing the impacts of pest species in a plant production and plant biosecurity context. Plant biosecurity refers to the research, procedures and policies that cover the exclusion, eradication or effective management of the risks posed by the accidental or intentional introduction of alien plant pests (see Gordh and McKirdy 2014, and references therein for a thorough exploration of the discipline). While we recognise the importance of the environmental and human health components of impact when defining the total impact of a pest species, here, we focus specifically on plant production and trade metrics, which are predominantly economic, socio-political and management related. The utility of the metric

system is tested through application to pest case studies and the proposal of a preliminary scoring system to aid comparison of pest scenarios. To the best of our knowledge, this is the first time a framework has been developed that articulates, defines and classifies the impacts of pest species – both alien and native; historical, current and potential – for the full range of plant production systems (inclusive of horticulture, field crops, pastures and forestry).

Materials and methods

The identification of key plant pest impact metrics and development of our classification system was an iterative process involving literature analysis, expert input, and pest risk assessment practitioner validation. Our metrics are identified throughout the text using capitals for the first word and italics. Primarily, metrics were derived from economic assessment parameters used to analyse plant biosecurity impacts (see Cook and Fraser (2015), Cook *et al.* (2012; 2015) and references therein), direct and indirect pest effects identified in the ISPMs of the IPPC (ISPM 2 (FAO 2016a), 4 (FAO 2016b), 5 (FAO 2016c) and 11 (FAO 2016d)), and the structure and insight of recent environmental impact classification schemes (Blackburn *et al.* 2014; Kumschick *et al.* 2015a; Nentwig *et al.* 2010; Ojaveer *et al.* 2015; Parker *et al.* 1999). The environmental and socio-economic impact classification EICAT (Hawkins *et al.* 2015) and SEICAT (Bacher *et al.* 2018) schemes were particularly influential in the development of our system, with some key differences. Most notably in our system we have chosen to focus on predominantly measurable economic impact values, with a broader scope to assess both alien and native pest species within the one system. We chose also to advocate for metric amalgamation over deferring to the most severe impact (e.g. Blackburn *et al.* 2014) when considering overall classification. Here, we present a brief summary of how the Plant Pest Impact Metric System (PPIMS) was developed, with further detail provided in Supplementary Information S1 – Guidelines.

Practitioner engagement

Discussions with pest risk assessment practitioners in Australia and New Zealand were used to identify and validate plant pest metric selection and criteria development. These practitioners included researchers, as well as industry, provincial and national representatives, comprised of the 18 authors of this paper and an additional 12 contributors external to the authorship team. Practitioners were clear that the metric system developed should allow for transparency, flexibility in development and application, and harmonisation of pest management and prioritisation across multiple scales and jurisdictions. Practitioners were given the opportunity to comment and contribute at all stages of development, with many providing pest classification examples for preliminary validation and iterative metric development.

A survey component of this study was prepared through consultation with CSIRO's internal ethics committee (application number 062/15) and key stakeholders. Where individuals are identifiable they are either part of the authorship for the paper, project team members who chose not to be authors, or were plant biosecurity practitioners advised orally at a workshop and/or in writing via email correspondence that by participating in the workshop and providing their written materials that this comprised consent to use their feedback in the development of these guidelines and this manuscript.

Taxonomic and spatiotemporal scope

An advantage of the system we present is that it is not limited to classifying alien species, and can be applied to categorisation across taxonomic boundaries and spatiotemporal scales. By clearly defining taxonomic boundaries and spatiotemporal scales of the pest

scenario (or potential pest scenario) from the outset of the assessment, all metrics can be scaled and defined appropriately in a clear and transparent manner. Both potential and current/historical impacts at relevant jurisdictional/spatial scales can be individually assessed and compared, or an overall assessment can be made. This allows for comparison of impacts across the full suite of plant pests, including insects and other arthropods, molluscs, pathogens and weeds, at differing levels of taxonomic complexity (e.g. a pathogen with or without its vector). All pests, whether native or alien, can be evaluated with our system, under different pest scenarios (e.g. impacts over varied time periods and/or in different areas/under different cropping regimes).

Class category/magnitude delineation

Each metric was delineated into one of five clearly defined classes, ranging from minimal concern to massive (sensu Hawkins *et al.* 2015) (Fig. 1). Each class increment was scaled exponentially to allow for easier discrimination between impacts and to smooth differences arising as a result of uncertainty in the data (epistemic, linguistic or otherwise). Metrics can be categorised as data deficient (DD) (sensu Blackburn *et al.* 2014) or as not evaluated (NE), as they are not applicable to the pest scenario in question. For example, assessing primary response costs may not be relevant to native or long-established pests.

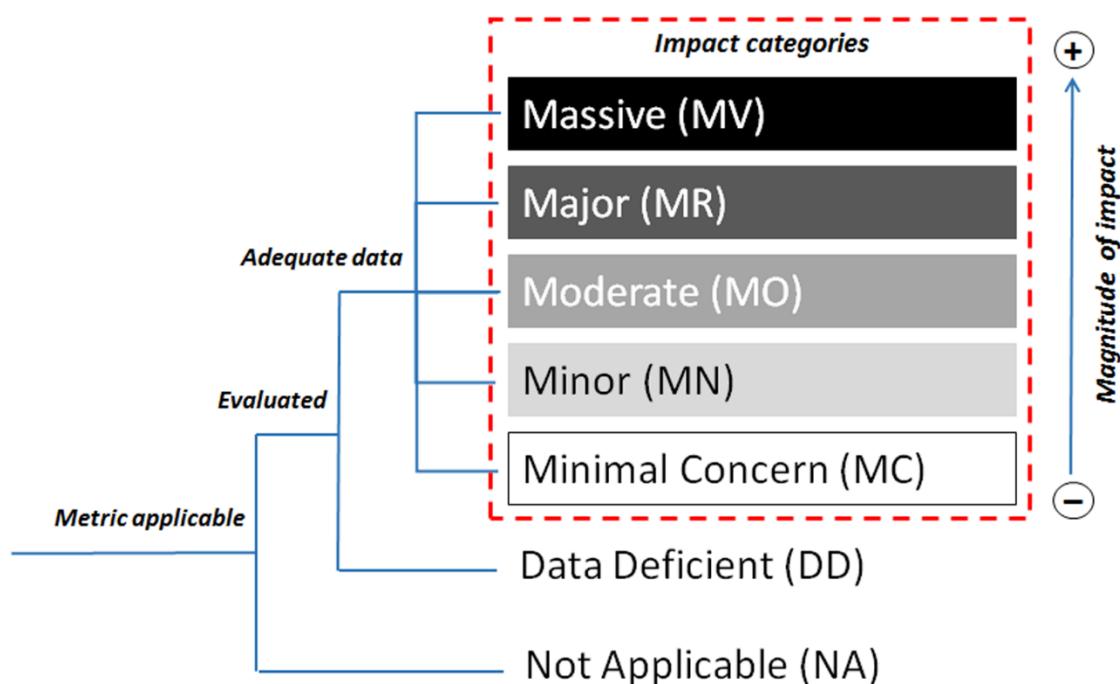


Figure 1. The different categories in the plant pest impacts metric system (PPIMS), and the relationship between them (modified from Blackburn *et al.* (2014)). Descriptions of each of the categories for each of the metrics are provided in the PPIMS guidelines (Supplementary Information S1).

Disruptor and nested metrics

Metrics which the authors considered likely to influence overall impact classification by at least twofold, when amalgamated with other metrics (see our proposed scoring system section for further detail), were identified as disruptor metrics (Table 1). They were selected by the authors based on their collective expertise in plant biosecurity and risk assessment, literature analysis, and validated through discussions with pest risk practitioners. Metrics identified as strongly influencing or interacting with one another were also nested below their

most overarching “primary” metrics, to avoid double-counting and pseudo-replication in any final integrative analyses.

Table 1. Plant pest impact metric system (PPIMS) metric descriptions. Disruptor metrics are identified in italics and with an asterisk (*).

Metric		Brief description
Spatiotemporal		
A	Distribution	Geographic range of the pest, based on political boundaries such as states or provinces.
B	Maximum area affected	Percent area of the assessed host(s) affected by the pest.
C	Frequency	How often the pest reaches large enough population size to cause discernible damage.
D	<i>*Reversibility</i>	Temporal measure of how quickly a pest can be eradicated or managed effectively.
Market-driven		
E	<i>*Host crop value</i>	Percent of the total plant industry value that is affected by the pest.
F ₁	<i>*Market access</i>	Changes in export conditions and trade in response to a pest being present.
F ₂	Alternate market	Identifies whether alternate markets are open when trade with original markets is restricted.
F ₃	Loss of pest free status	Percent value of the cropping area that loses pest free status.
F ₄	Treatments	Changes in existing pest or disease control measures to guarantee market access.
G ₁	Price discount	Percent change in the prevailing price of the crop (or crop product).
G ₂	Quality loss	Percent reduction of cosmetic, physical or food safety properties.
Primary response		
H	Investment	Percent measure of the cost of a response in relation to the value of the affected industry.
I	Yield loss	Percent yield loss for affected crops.
J	Success	To what degree eradication or containment efforts have been successful.
Mid- to long-term response		
K ₁	Economic injury level (EIL)	How much the pest density differs proportionally from the EIL (if known).
K ₂	Control costs	Proportional cost of control measures used to manage the pest to an acceptable level, but excluding eradication efforts.
K ₃	Yield reduction	Measure of the yield loss which occurs despite control measures being put in place.
L ₁	<i>*Feasibility of management</i>	How easily the pest can be managed.
L ₂	Cultivar loss	Percent losses of cultivars, which may be “lost” or rendered less profitable due to susceptibility.
L ₃	Cultivar recovery	How quickly an industry may be able to deploy resistant/tolerant cultivars to ensure production continues, despite pest presence.

Metric criteria and classification

Twenty metrics were identified and assigned to one of four key metric types: spatiotemporal, market-driven, primary response and mid- to long-term response (**Table 1**). Metrics are identified throughout the manuscript by using capitals for the first word and italics. Disruptor metrics are further identified with an asterisk (*).

Four metrics were identified that fell primarily into the spatiotemporal metric type category: *Distribution*, *Maximum area affected*, *Frequency* and **Reversibility* (i.e. possibility/speed of eradication). They were grouped as such as they were recognised as components of plant pest impacts which are largely influenced by space and time. Impacts of pest species can vary greatly across space and time (see Ricciardi *et al.* 2013, and references therein), as a result of (but not limited to) pest biology, environmental variability in habitat suitability and vulnerability, seasonality and weather fluctuations, changing agricultural practices, and level of synchrony between pest arrivals and deployment of detection resources (Caley *et al.* 2015; Leung *et al.* 2012).

Seven metrics were identified as primarily market access metric types: **Host crop value*, as well as six other metrics nested under two broad groups: **Market access*, with *Alternate market availability*, *Loss of pest free status* and *Market access treatments* nested; and *Crop price discount*, with *Quality loss* nested. Importantly for PPIMS, the presence of pests can affect access to international and domestic markets. Market-driven metrics are therefore among some of the most important and disruptive metrics, due to their economic importance and susceptibility to socio-cultural and political influences. Should demand for a particular plant product or crop fall in the marketplace, the economic incentives to produce the crop are reduced and farmers may choose to lose the entire crop rather than take it to market at a loss, especially if it is already under significant pest pressure.

Three metrics were identified as primary response metrics: *Primary response investment*, *Yield loss* and *Primary response success*. The primary response phase occurs shortly after an incursion event, and most commonly consists of eradication and/or containment efforts. This period may end as a result of a successful eradication or due to a pest moving into a longer-term management phase.

Six metrics were identified as mid- to long-term response metrics: grouped under *Economic injury level (EIL)*, which incorporates *Control costs*, and *Yield reduction despite control*, and **Feasibility of management*, which incorporates measures of *Cultivar loss* and *Cultivar recovery*. These metrics are applicable to well-established pests, or those pests transitioning from a primary response phase into longer term management.

Amongst all metrics, **Host crop value*, **Market access*, **Feasibility of management* and **Reversibility* were identified as disruptor metrics. The selection of these metrics was based on recognition of the importance of economics and market influences on the overall impacts of plant pests, particularly in the case of **Host crop value* and **Market access*; and on the importance of management tools and the role of pest biology in mitigating these impacts, in the case of **Feasibility of management* and **Reversibility*. Further detail on metric selection and classification is provided in Supplementary Information S1 – Guidelines.

Scoring system

We propose a mixed additive/proportional scoring procedure for PPIMS, weighted to favour disruptor metrics (Box 1). The method was selected following an assessment of a range of differing scoring methods (see Supplementary Information S2 – Interactive Metric Table), as it is capable of handling piecemeal and disparate data inputs, to give a measure of impact in the face of high uncertainty. To facilitate development of the scoring system and allow for rapid interpretation of different components of impact, metrics were assigned to five metric groups: disruptor, spatiotemporal, market-driven, primary response and mid- to long-term

management, which can each independently have a score calculated following nested metrics being averaged. Nested metrics are averaged (Step 1, Box 1), with equal weighting to all answered metrics, to present a singular score for each of these groups of metrics. This effectively results in a maximum of 12 scores, rather than 20 (the total maximum number of metrics). Disruptor metrics are accounted for both within the disruptor and their relevant metric group, in order to account for their greater influence on the realised impact of a pest, by at least twice that of non-disruptor metrics.

Box 1. Scoring system. See Table 1 for metric coding (A-L₃).

Calculated only from answered metrics and scaled accordingly.

Step 1. Average nested metrics

$$\bar{F} = \frac{1}{n} \sum_{i=1}^n Fi \quad \bar{G} = \frac{1}{n} \sum_{i=1}^n Gi \quad \bar{K} = \frac{1}{n} \sum_{i=1}^n Ki \quad \bar{L} = \frac{1}{n} \sum_{i=1}^n Li$$

Step 2. Average all metrics

$$\overline{metrics} = \frac{1}{n} (A + B + C + D + E + \bar{F} + \bar{G} + H + I + J + \bar{K} + \bar{L})$$

Step 3. Average all disruptors

$$\overline{disruptors} = \frac{1}{n} (D + E + \bar{F} + \bar{L})$$

Step 4. Average all metrics and all disruptors

$$\overline{all} = \frac{1}{n} (\overline{metrics} + \overline{disruptors})$$

Step 5. Calculate final score

$$\text{Final score} = \frac{\overline{all}}{4}$$

Each metric class is assigned to a rank of zero to four, to indicate the increasing level of impact for each class: minimal concern (0), minor (1), moderate (2), major (3) and massive (4) (Figure 1). These scores are then averaged across the number of metrics answered, accounting for nested metrics (Step 2, Box 1; Supplementary Information S1 and S2), so there is no direct disadvantage or negative bias toward data deficient or non-evaluated metrics, and the results are presented as a *proportion* for each metric group. An overall score is calculated by taking the average of the disruptor group score and the combined metric scores (remaining after nested metrics are grouped as mentioned above) (Steps 3–5, Box 1), effectively weighting the score to a higher or lower score in the disruptor group. These proportions are then assigned an overall impact classification of negligible (0), low (> 0–0.25), moderate (> 0.25–0.50), high (> 0.50–0.75) and extreme (> 0.75). Standardised risk assessment terminology (i.e. negligible, very low, low, moderate, high, and extreme) is adopted for these overall impact classifications, to assist integration of the measures with existing pest risk assessment frameworks (Ojaveer *et al.* 2015).

Score uncertainty

We propose that score uncertainty is represented as a measure of the proportion of metrics recorded as data deficient (DD), exclusive of the double-counting of disruptor metrics and evaluation of nested metrics. In other words, as a proportion of the 20 original metrics, minus any metrics that are not evaluated (NE). Metrics may not be evaluated (NE) if they are

deemed to not be applicable to the pest scenario in question. This would be the case when assessing a pest species that has been established for some time and for which the data on primary response is either unavailable or unimportant (see Supplementary Information S1 for further information). Ideally, as expert input quality, data sources and assessment skill improve, this measure of uncertainty will be reduced with successive assessments.

Metric confidence score

In addition to the score uncertainty, assessors can also account for the uncertainty in the classifications of those metrics that have been answered, hereafter referred to as the metric confidence score. We propose here that assessors use the measures of metric confidence as described by (MacLeod 2011) (as cited by Blackburn *et al.* 2014; and Hawkins *et al.* 2015), based on standard approaches used by the Intergovernmental Panel on Climate Change (IPCC) (Mastrandrea *et al.* 2010) and EPPO (Holt *et al.* 2012; Kenis *et al.* 2012). This confidence score reflects the practitioner's confidence in the availability and reliability of evidence, the type of data used to make the assessment, the spatial scale over which the data were recorded, and whether or not the evidence is contradictory (Hawkins *et al.* 2015). It is categorised into three levels: high (~ 90 % chance of the given score being correct), medium (~ 65–75 % chance), and low (~ 35 % chance) (Hawkins *et al.* 2015), and can be provided for each metric individually or for the assessment overall. We present an overall assessment in our case studies section below.

Applying the impact metric system

Comprehensive guidelines on how to interpret and use PPIMS can be found in Supplementary Information S1 – Guidelines. In brief, the taxonomic and geographic scope of the pest scenario being assessed needs clarification at the outset of the pest assessment. At the very least, pest and host details (including common and scientific names), the area and time period being assessed, name of the assessor(s) and any other clarifying notes should be recorded (Table 2, Supplementary Information S1 and S2). Such documentation, used to justify the assessment and provide relevant information about the pest and its impacts, will assist future risk assessment and risk management strategies, as well as provide transparency to the overall process (Hawkins *et al.* 2015).

As a means of a preliminary and iterative calibration/validation, the metric system was applied to several case studies involving bacteria, fungi, insects, nematodes and viruses that represented both horticultural and forestry pests, under both current and future scenarios.

Table 2. Exotic plant bacteria impacts – Spatiotemporal fluctuations (identified in bold)

Pest scenario	Temporal scale change		Spatial scale discrimination	
Pest:	<i>Pseudomonas syringae</i> pv. <i>actinidiae</i> (Bacteria)		<i>Xanthomonas citri</i> subsp. <i>citri</i> (Bacteria)	
Host(s):	<i>Actinidia deliciosa</i> , Green kiwifruit, less susceptible; <i>A. chinensis</i> 'Hort16A', Gold kiwifruit, highly susceptible		<i>Citrus</i> spp., including mandarins, oranges, lemons, limes and grapefruit, of varying susceptibilities	
Area:	North Island, New Zealand		Queensland, AU	Australia
Time period:	2010–2012	2010–2015	2004–2009	
Reference ^:	Table S28	Table S29	Table S30	Table S31
Impact class (score) ^a:	High (0.705)	High (0.674)	Moderate (0.465)	Moderate (0.426)
Uncertainty (DD)	0.00	0.05	0.23	0.21
Confidence	Medium	Medium	Medium	Medium
(Table continued below)				

(Table continued from above)				
Pest scenario	Temporal scale change		Spatial scale discrimination	
Metric	Classification ^b			
Disruptor ^c	0.625	0.625	0.500	0.500
Spatiotemporal	0.938	0.938	0.375	0.250
Distribution	MV	MV	MN	MN
Maximum area affected	MV	MV	MO	MN
Frequency	MV	MV	MO	MO
*Reversibility	MR	MR	MN	MN
Market-driven	0.458	0.396	0.438	0.458
*Host crop value	MR	MR	MR	MR
*Market access	MO	MN	MN	DD
Alternate market availability	MO	MN	DD	MC
Loss of pest free status	MV	MV	MO	MN
Market access treatments	MO	MN	NE	MN
Crop price discount	MC	MC	DD	DD
Quality loss	MC	MC	DD	DD
Primary response	0.917	0.750	0.500	0.417
Primary response investment	MV	MR	MV	MR
Yield loss – primary response	MR	MO	MO	MO
Primary response success	MV	MV	MC	MC
Mid- to long-term management	0.750	0.750	NE	NE
EIL	NE	DD	NE	NE
Control costs	NE	MO	NE	NE
Yield reduction despite control	NE	MV	NE	NE
*Feasibility of management	MR	MR	NE	NE
Cultivar loss	MR	MR	NE	NE
Cultivar recovery	MR	MR	NE	NE

[^] See Supplementary Information S1. Plant Pest Impact Metric System (PPIMS) Guidelines

^a See Scoring system section in text

^b Minimal concern (MC) = 0, Minor (MN) = 1, Moderate (MO) = 2, Major (MR) = 3 and Massive (MV) = 4. NE = Not Evaluated. DD = Data Deficient

^c As calculated from Disruptor metrics, identified in italics and with an asterisk (*)

Results

Two bacterial case studies are detailed here, as they are demonstrative of how assessments can change over time (kiwifruit canker in New Zealand) and space (citrus canker in Australia) (Table 2 and Supplementary Information S1 Tables S28 – S31). Further case studies and examples can be found in Supplementary Information S1 and S2.

Kiwifruit Canker – *Pseudomonas syringae* pv. *actinidiae* (Psa) – New Zealand

Pseudomonas syringae pv. *actinidiae* (Psa) is the cause of kiwifruit canker disease. It is a bacterial pathogen of global importance to kiwifruit production (Vanneste 2013). Since first being detected in Japan in the late 1980s (Takikawa *et al.* 1989), the pathogen has spread to almost all major kiwifruit growing regions, where it seriously limits production of gold kiwifruit and impacts growers substantially (Vanneste 2013). Symptoms of the disease vary from serious cane die-back and vine death, to less serious leaf spotting and flower wilts, accompanied by flower and bud drop (Serizawa *et al.* 1989). Gold kiwifruit cultivars (especially *A. chinensis* 'Hort16A') are more susceptible to the pathogen than the cultivars of the classic green kiwifruit (*A. deliciosa*) (Froud *et al.* 2015).

Kiwifruit is a major horticultural sector in New Zealand, accounting for more than 2% of the total plant production value (NZIER 2016). Psa had been of increasing concern as an emerging threat to the industry since its rapid spread in the period 2008–2010 across Europe (Scortichini *et al.* 2012; Vanneste 2012). The bacterium was first detected in New Zealand in late 2010, infecting both gold (*A. chinensis* 'Hort16A') and green (*A. deliciosa* 'Hayward') kiwifruit plants (Everett *et al.* 2011), and had spread to all kiwifruit growing regions on the North Island of the country by 2012 (Cunty *et al.* 2015; Vanneste *et al.* 2013). It has had a massive impact on the gold cultivar 'Hort16A' in New Zealand, with destruction of entire diseased canopies and vines (Froud *et al.* 2014), which accounted for 30% of the export kiwifruit value in New Zealand at that time (Greer and Saunders 2012). In 2012, the cost of Psa to the New Zealand kiwifruit industry was estimated to be approximately \$126 million (Froud *et al.* 2014), with loss of market access for all kiwifruit nursery stock (Table S28). Large government and industry investments were made to contain and destroy heavily infected vines during the initial response period, which we define as covering 2010 - 2012 (Table S28).

In 2012, the rapid and wide adoption of Psa tolerant kiwifruit varieties (Greer and Saunders 2012) revitalised the industry and empowered growers to continue profitable production and make an effective transition to a long term management strategy for the pathogen. This, in concert with improved and locally adapted management strategies (Vanneste 2013) and the discounting of initial incursion costs over time (Table S29), resulted in the overall impact of the pathogen reducing over time (Table 2). Recent evolution of copper resistance in Psa in New Zealand (Colombi *et al.* 2017) could prove problematic in relation to *Feasibility of management in the coming years, which could increase the magnitude of this metric and potentially the overall impact score above that assessed for the period of 2010–2015 (Tables 1, S29). This case study demonstrates that our metric system is able to reflect the influence of time and adaptive management in reducing pest impact in the case of Psa in New Zealand, with a reduction of pest impact when assessed over a larger time period (Tables 2, S28 and S29).

Citrus Canker – *Xanthomonas citri* subsp. *citri* – Australia

Xanthomonas citri subsp. *citri* is a bacterial pathogen that causes citrus canker disease. This pathogen is of global importance to citrus production (Das 2003). Originating in tropical areas of Asia (Das 2003), the pathogen has spread to almost all major citrus growing regions, where it causes serious economic losses and impacts on trade (Das 2003; Gambley *et al.* 2009; Gottwald *et al.* 2002). Cankorous, raised lesions on fruit and stems are typical of the disease, and are often accompanied by water soaked lesions with yellow halos on leaf tissue (Das 2003; Gambley *et al.* 2009). The pathogen has a wide host range within the family Rutaceae, including many commercial citrus varieties and root stocks with varying

susceptibilities, with grapefruit (*Citrus paradisi*), limes (*C. aurantifolia*), trifoliate orange (*Poncirus trifoliata*) and their hybrids amongst those most highly susceptible (Das 2003).

Citrus is a highly valuable horticultural crop in Australia, accounting for more than 1.5% of all plant production value (Australian Bureau of Statistics 2015) (Australian Bureau of Statistics 2013; 2014), and is considered a high priority pest by the citrus industry (Plant Health Australia 2004). The bacterium has been detected and eradicated at least twice in Australia (Commonwealth of Australia 2019), with the two of the most well-known eradications taking place in the Northern Territory in the early 20th century (Broadbent *et al.* 1992) and in Queensland in the early 21st century (Gambley *et al.* 2009). Both eradications adopted a scorched earth policy, which provided the basis for selecting the classification criteria for the *Yield loss – primary response* metric (see section 2.2.3.2 in Supplementary Information S1 – Guidelines, for further detail). The latter incursion, detected in 2004, is the focus of this case study (Tables 2, S1.3 and S1.4) and subsequent eradication was estimated to have a net benefit of approximately AU\$70 million for the state of Queensland alone (Gambley *et al.* 2009). However, the Queensland citrus industry represents only a small proportion of total national production area and value, which in 2017 was estimated to be worth just around 1 % (Plant Health Australia 2017). The assessments made using our metric system could discriminate between pest scenarios at different spatial scales, with citrus canker having a greater impact at the provincial level of Queensland (Tables 2 and S1.3), than at the national Australian scale (Tables 2 and S1.4). This was largely due to the order of magnitude difference in *Maximum area affected*, which then had roll-on effects to other metrics. For example, proportional areas and costs were defrayed, and therefore reduced in magnitude, when assessed at the national level for metrics such as *Loss of pest free status* and *Primary response investment*. The system also accurately reflects when a successful eradication has been conducted, as the mid- to long-term management group of metrics are no longer relevant, as shown by the NE designation for both the citrus canker examples (Table 1).

Assessor knowledge and uncertainty

The system captured differing levels of assessor knowledge and uncertainty (i.e. DD) in both case studies, as well as changes in what metrics were considered not applicable to an assessment, and were therefore not evaluated (NE). For example, the citrus canker assessments (Tables S30 and S31) were conducted by independent assessors, and captured differences in their knowledge and uncertainty for three of the Market-driven metrics (Table 2), **Market access* (Minor in Table S30 to DD in Table S31), *Alternate market availability* (DD in Table S30 to Minimal Concern in Table S31) and *Market access treatments* (NE in in Table S30 to Minor in Table S31).

Discussion & Conclusions

The plant pest classification system proposed here lays the foundation for a standardised method to evaluate, compare and potentially predict the magnitudes of pest impacts in plant production systems. It classifies pests across taxonomic and spatiotemporal boundaries, enabling assessors to make useful comparisons across several plant pests at any one time. Our work demonstrates the value of integrating plant protection science with invasion biology, to derive a comprehensive measure of pest impact in agroecosystems that can be utilised by all plant biosecurity stakeholders. This integration has effectively allowed us to develop a classification system that overcomes a lack of standardised impact and crop loss methodologies within plant biosecurity.

We recommend that plant pest impact assessments are:

- (a) scaled to clearly defined spatiotemporal and taxonomic aspects of a pest scenario,

- (b) focused on production specific metrics (largely economic and management, while making use of established environmental and emerging socio-cultural impact systems for these additional value sets),
- (c) weighted to, and recognise, “disruptor” metrics, and,
- (d) based on semi-quantitative classes (or quantitative, if possible), with predominantly numerical boundaries which indicate an increase in impact effect by an order of magnitude or exponential difference.

Through a thorough review of the literature and iterative feedback with plant industry representatives and pest risk assessment practitioners we were able to parameterise the majority of metrics (18/20; Table S1) with numerical indices, for example, percentage change, kilometres of spread, years to eradication. Where numerical guidelines are stated in other systems (e.g. section 6.01 in EPPO Standard PM 5/3(5) (EPPO 2011)), they are not provided within a classified metric framework such as what we present here. While that is understandable given the uncertainty around setting numerical boundaries for different crops and growing conditions, as discussed by EPPO (2011), a lack of standardised boundaries across the whole of plant production or even within key crops or industries, prevents meaningful comparison among assessments. Thus, similar to Hewitt *et al.* (2011), we propose a mix of numerical and qualitative guidelines to assess pest impacts. We argue that the inclusion of numerical boundaries contributes to a much more transparent and robust metric system. This means that overall assessments are less likely to be limited by the quality of available data when classified within broad categories such as those laid out in our classification criteria. Additionally, the system is capable of being further refined to provide more meaningful scoring and amalgamation methods.

We have shown through application of the system to classifying Australian (citrus canker) and New Zealand (Psa) case studies that our system can discriminate between species known to have different impacts across both space and time (Tables 2, S28–S31). Our preliminary assessments indicate that the impact of Psa on the kiwifruit industry in New Zealand has reduced over time, with impact classification lowering in five metrics, including one disruptor metric (**Market access*) (Tables 2, S28 and S29). Similarly, assessment of the citrus canker incursion into Australia in 2004 showed a greater impact in Queensland in at least three of the metrics, compared with the impact at a national level (Tables 2, S30 and S31). Notably, there were three instances in each case study where the classification of a metric changed from being data deficient or not evaluated to an impact class, and from not evaluated to data deficient. Such changes were indicative of the shift from a primary response to longer term management in the case of Psa, while for citrus canker they may indicate either (a) differences in how markets are accounted for at different jurisdictional levels or (b) differences in assessor interpretation of the metrics (which were undertaken by two independent groups, see Tables S30 and S31). While differences in metric classification across assessments may generate some confusion when making comparisons, it is also a valuable insight into how different stakeholders may perceive and assess risk, allowing practitioners to use the system as a communication tool and providing a transparent decision-making process that can be interrogated by, and discussed with, other stakeholders.

A standardised and common plant pest metric system, such as that presented here, provides a critical foundation to support harmonised pest risk prioritisation. Our metric system is a stand-alone tool that can be integrated to improve impact assessments within currently used risk assessment and prioritisation frameworks. If applied widely by agricultural and plant biosecurity stakeholders, it has the power to transform relationships and

harmonise pest management across multiple spatiotemporal scales and jurisdictions. Such integration should result in fair and transparent allocation of resources in a timely manner and improve cross-disciplinary and cross-sectoral understanding of priorities. Our work demonstrates the value of integrating plant protection science with invasion biology, to derive a comprehensive measure of pest impact in agroecosystems that can be utilised by all plant biosecurity stakeholders.

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Supplementary information

(available at DORA, <https://www.dora.lib4ri.ch>)

S1. Plant Pest Impact Metric System (PPIMS) Guidelines.

Detailed guidelines for each metric, how to apply the system at differing spatiotemporal scales, how the metrics may be integrated and scored effectively and how PPIMS outputs may be used within a plant biosecurity and risk assessment context.

S2. Plant Pest Impact Metric System (PPIMS) Interactive Metric Table. Includes a blank assessment sheet with embedded scoring systems, 15 example pest classifications and a comparison table of these examples using different scoring methods.