Digital Identification Tools for Plant Biosecurity: A Review
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A Review of Digital Identification Tools for Plant Biosecurity

Content

1. Background to digital identification tools (DITs)

Efficient and accurate identification of potential pest organisms is fundamental to plant biosecurity; it can begin on the farm, be necessary for pre-clearance prior to shipping, be critical during border inspections, and be necessary for the management of an invasive pest[1] before it has established. As global trade has increased, the stakes have become higher. More trade means greater movement of cargo and commodities, together with the pests that can come with them. With this increased risk, many countries have stepped up biosecurity requirements; markets often require certain phytosanitary standards to be met prior to shipment to help prevent the spread of potentially invasive and damaging pests **Keller et al., (2011)**. Most countries also perform border inspections, sometimes including pre-clearance or pre-departure inspections and/or treatments at the origin, in transit, or upon arrival.

This increase in the risk of pest introductions comes at a time when the number of taxonomists is declining **Wheeler, Q D, (2013)**; fewer taxonomists are being trained, particularly those able to identify and distinguish regulated pests from similar organisms. Although many new and faster technologies have been developed to help streamline pest identification, including molecular and biochemical methods, traditional morphological identification is still the primary method used in practice. The good news is that emerging computer technologies could take morphological identification into a new era. The biosecurity challenge is how to meet an increased need for pest identification given the continuing decline in available taxonomic expertise.

Printed pest and disease brochures and leaflets, training of para-taxonomists, new molecular identification tools, farmer field schools, and plant clinics provide some answers to improving the capacity to identify pests. This review focuses on the increasing role that digital identification tools (DITs)[2] can play in meeting the need for rapid, accurate pest identification and diagnostics. There are three specific activities that these DITs can address – pest management in the field (including pest and natural enemy identification); quarantine (invasive pest identification in transport and products); and education and training of students and practitioners.

The information and communication technology (ICT) revolution over the past 40 years has involved hardware development, from large computers to desktop devices and smartphones, combined with a surge in software technologies, such as the Internet, Wi-Fi, and smartphone apps. This ICT advancement has provided the foundation for developing a wide range of DITs, offering alternative means for biosecurity officials, testing laboratories, and others to obtain pest identification support. For instance, **IDaids**, an online database of recommended DITs, described later in this review, listed over 6057 digital resources as of April 2023.

In the following section (2) of this review, the different types of DITs that already exist are reviewed, together with the role they can play to support identification and diagnosis of pest organisms for biosecurity purposes, as well as for plant protection more generally. These tools include those providing remote connections with experts, digital identification guides, identification and diagnostic keys, image databases, and emerging artificial intelligence (AI) applications.

The next section (3) describes the ways these tools are currently being developed and used by testing laboratories and by government and other agencies. Two case studies (one in the United States and one in Europe) indicate the strategies used to identify the need for identification tools, as well as how they are being developed in combination with other databases, images, and fact sheets to meet the different needs of quarantine officers, testing laboratories, and other inspection activities related to trade. Two further examples are concerned particularly with international collaborative DIT projects. The first project concerns the development of digital tools and resources for seed identification, while the second concerns an international collaborative effort by several thrips taxonomists to develop a series of identification tools for thrips to meet the needs of specific countries and regions.

The final section (4) of this review considers the lessons we have learned about the development and use of DITs and the need for greater integration with other tools, such as lab-based molecular techniques, image databases, mapping tools, pest reporting, and online and interactive training. The review concludes with a discussion of the role of DITs in the future, including the potential of image recognition software, using AI, and the implications this could have for the role of human taxonomic and diagnostic expertise.

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[1] The term “pest” is used in the sense of the broad **FAO** definition – “Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants and plant products, materials or environments and includes vectors of parasites or pathogens of human and animal disease and animals causing public health nuisance”.

[2] [The term Digital Identification Tool (DIT) is used throughout this chapter to include tools for identification and diagnostics, in the sense of an “identification” based on crop symptoms].

2. A review of existing types of DITs

The development of ICT links that facilitate communication between an expert and a farmer or government advisor is the first DIT technology to be considered. This is followed by fact sheet tools that are delivered online and as smartphone apps, providing a new medium that complements information previously provided by published (hard copy) pest and disease booklets or guides. Digital identification keys based on traditional pathway or dichotomous keys are described next, followed by interactive matrix keys used for pest identification and symptom-based crop diagnostics. Specialised image galleries and databases can provide identification tools in their own right, as well as providing valuable support to other DITs. A brief account of some examples of emerging AI applications to pest identification completes this initial review.

2.1. DITs that link practitioners directly to experts

Digital tools that link biosecurity officials, crop advisors, and farmers with a taxonomist or experienced field expert are of two types: remote diagnostics and community networks. For biosecurity officials and crop advisors in remote regions, such tools may be the only way they can obtain expert advice to identify intercepted organisms or diagnose crop symptoms.

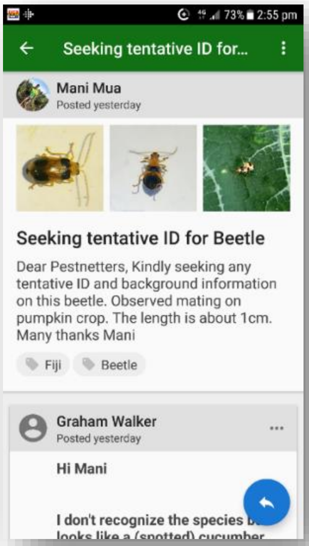
Remote diagnostics is a web-based, real-time, interactive advisory system based on an interlinked microscopy network or internet connection. It enables quarantine officers to display the specimen concerned to relevant experts via the Internet, allowing the expert to ask for different aspects of the specimen to be viewed to help make an identification.

Remote diagnostic systems have been developed in Australia and Southeast Asia for use in national biosecurity operations. A similar system is currently being used by the Ministry of Primary Industry in New Zealand to support the identification of intercepted specimens in Pacific Island countries **Thompson et al. (2011)**.

Providing real-time diagnostic advice remotely can be affected by slow internet speeds and by difficulties in scheduling a link convenient to both parties on different time zones. Perhaps a more important role that remote microscopy can play is to create 'virtual taxonomic laboratories' that enable taxonomists in different locations and countries to work together, view each other's specimens, and share information in real time.

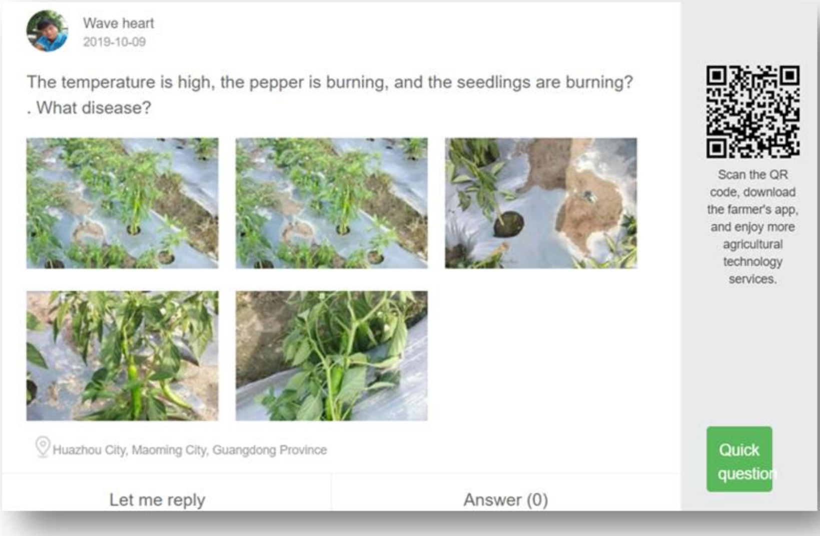
Virtual interactions between personnel in plant protection labs in Australia and Thailand are also facilitating mutual education and collaboration. This is especially valuable for dealing with and confirming specific exotic specimens and biosecurity threats.

Community identification and diagnostic networks provide another way of linking practitioners to taxonomists or other experienced field experts. Members of a digitally connected community can seek help to identify a suspected pest organism or diagnose a symptom of pest damage by submitting a request to the community online or via a smartphone/tablet app. A response from one or more experts (or other members of the community) is relayed back to the community in the same way.



PestNet, launched in December 1999, is an early example of a community network. Using a Yahoo Group email system, plant protection workers and farmers posted queries to the PestNet community, often attaching photographs of a detected organism or observed symptoms. Experts and other members of the community then sent an email response, which frequently led to further email discussion. PestNet was initially targeted at remote workers throughout the Pacific Islands, providing them with international biosecurity and plant protection support. Subsequently, the network expanded to Asia and other regions of the world.

The original PestNet service was later updated to an online service that supports both Android and Apple applications – **see screen shot** – and at the same time was combined with the digital fact sheet service Pacific Pests, Pathogens and Weeds, described in the following section. A similar community support network has been developed at Pennsylvania State University, USA, called **Plant Village**. Since this system has now included an AI component, it will be discussed later in section 2.6 with other AI support systems.



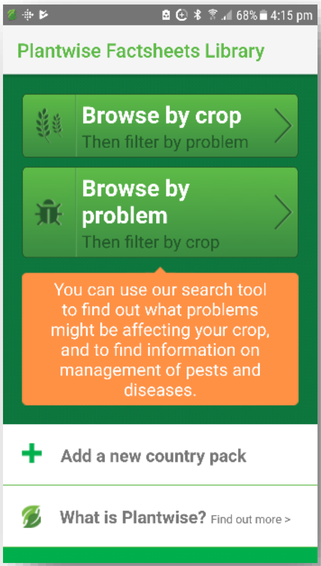
In China, a community-based system provides a free, open, and interactive agricultural service platform that uses mobile interconnection with agricultural experts who provide agricultural technology services to farmers. The question-and-answer function **– see screen shot** - provides technical training for both field technicians and farmers.

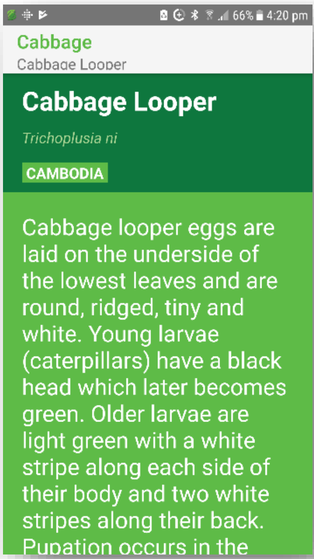
2.2. Digital fact sheets

The traditional approach of providing printed insect pest and disease fact sheets and brochures to farmers and their advisors helped with the early identification of pests not previously encountered. These fact sheets also provided information on what action needed to be taken, including notifying biosecurity authorities. Digital publications that are accessed online and/or via mobile phones are rapidly replacing paper-based fact sheets.

The two fact sheet systems described below are free to access online or with Android or Apple applications. Both operate in a similar way: providing information to help identify and diagnose pest problems, what treatment is likely to be appropriate, and the action needed to help prevent the problem occurring in the future. After selecting the crop concerned, a series of simple questions are asked, thereby characterizing the likely problem until a match is possible by comparing images. Both systems are updated frequently to provide up-to-date information to users.

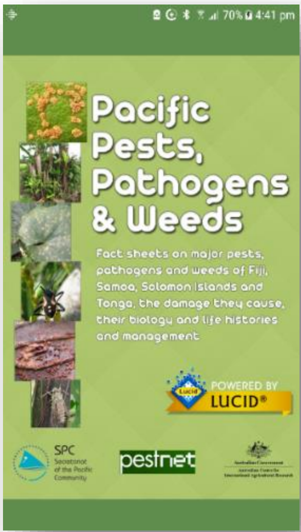
CABI - Plantwise Factsheets Library
Plantwise is a global programme designed to increase food security and improve rural livelihoods by reducing crop losses. Plantwise Factsheet apps (**Android** and **Apple}** are written by partners in Plantwise countries to give a quick outline of how to recognize a crop problem, a little background information about the problem, and step-by-step instructions on how to manage the problem – **see screen shots**.





Pacific Pests, Pathogens, and Weeds

This system, originally focussed on extension staff and lead farmers in the Pacific region, is also relevant to many crops in Southeast Asia. There are three free versions, an **online web based app**, and an **Android** and **Apple** mobile apps, where users have the option of viewing detailed fact sheets that are divided into sections on damage, biology, life cycle, and management – **see screen shots**. Mini-fact sheets provide the most relevant information that growers need for their purposes. As mentioned above, this system is now integrated with the PestNet community support system.



Fact sheet development tools

While the creation of digital fact sheets requires the input of taxonomists, agronomists, and other subject matter specialists, in many situations, technical software expertise for developing templates, sizing images, and dealing with digital tasks will not be available. To address this problem, and to provide more effective tools for producing and publishing digital fact sheets, two software tools have been designed and developed to specifically allow content experts to focus on the content of the fact sheet, choose specific designs, and leave the digital implementation to the underlying software.

Fact Sheet Fusion was originally designed to reduce the demand for technical support from identification key developers for such activities as:

- listing relevant topics and importing species information,
- importing and editing text,
- adding, editing, and sizing images (using a customized multimedia database),
- supporting a range of pre-determined outputs such as HTML, PDF, XML, and
- converting raw information into chosen fact sheet templates and performing related tasks, such as searching for and automatically creating hyperlinks to similar species.

A similar web-based tool, **Fact Sheet Manager,** developed by United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA APHIS) Identification Technology Program (ITP) for internal project use, is primarily to help create and maintain digital fact sheets associated with ITP projects involving USDA and other federal or contracted staff. Both these systems allow content experts to easily update the raw data in the tool and share this information with other users, who can then edit it for their specific location and language, and deploy the fact sheets as web pages, PDF leaflets, and attachments to keys.

2.3. Using a DIT to enhance dichotomous or pathway keys

Since the time of Linnaeus (1707-1778), dichotomous ("two-branching") or pathway keys developed and published by taxonomists, have provided a major support tool for species identification, including for biosecurity purposes. The typical form of a printed dichotomous key, shown in the box below, shows part of a key for determining the order to which an insect specimen belongs.

Box: Section of a dichotomous or pathway key to insect orders

1(a) Well-developed wings present, though often folded along body and inconspicuous – 2.
1(b) Wings absent, or present only as small, functionless pads or scales – 14…*etc*.

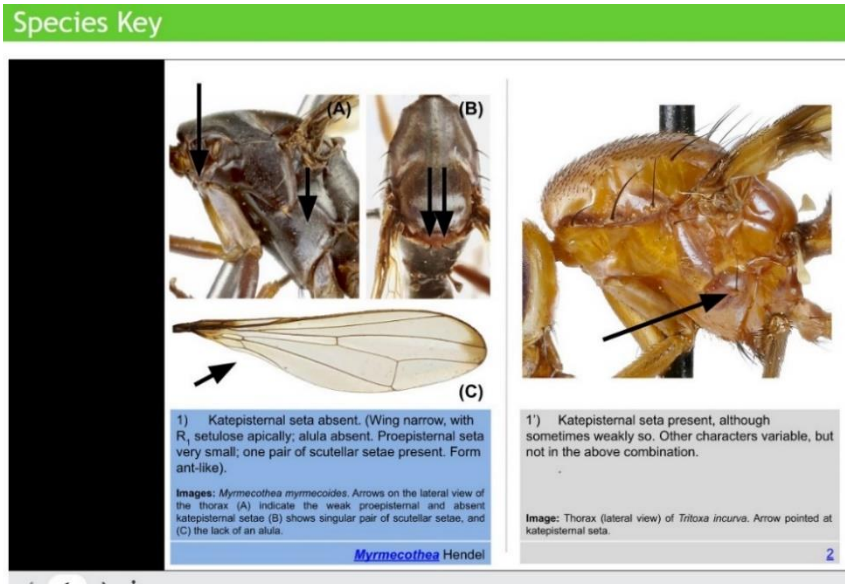
2(a) One pair of wings present – 3.
2(b) Two pairs of wings present; hind wings may be concealed beneath protective forewings – 4.

3(a) Forewings membranous; hind wings reduced to tiny club-like structures (halteres) – **Diptera**
3(b) Hind wings large, membranous; forewings reduced to tiny, strap-like structures – **Strepsiptera**

4(a) Forewings hard, opaque, in repose forming covers for hind wings; forewings entirely without branching veins or only at apex – 5…*etc*.
4(b) Forewings either transparent or with branching veins over most of surface, or not forming covers over hind wings – 8. ... *etc*.

The user follows a pathway through the key by comparing the features of the unidentified specimen with descriptions (and images) in the key. By choosing that component of a couplet that correctly describes the specimen, the user is led to the next relevant couplet. For instance, if components 1(a), 2(a) and 3(a) in Box 1 apply to a particular specimen, then it is identified as belonging to the order Diptera.

Pathway keys that are published on the web are likely to be easier to use than printed keys, particularly where images of features are included, and hyperlinks automatically bring up the next relevant couplet. For pathway keys that have a limited number of taxa, building and using the key can be relatively easy.



Screen shot: The initial couplet of a dichotomous key to the genera of Ulidiidae (Diptera: Tephritoidea) of the United States and Canada. Wallace C (2021)

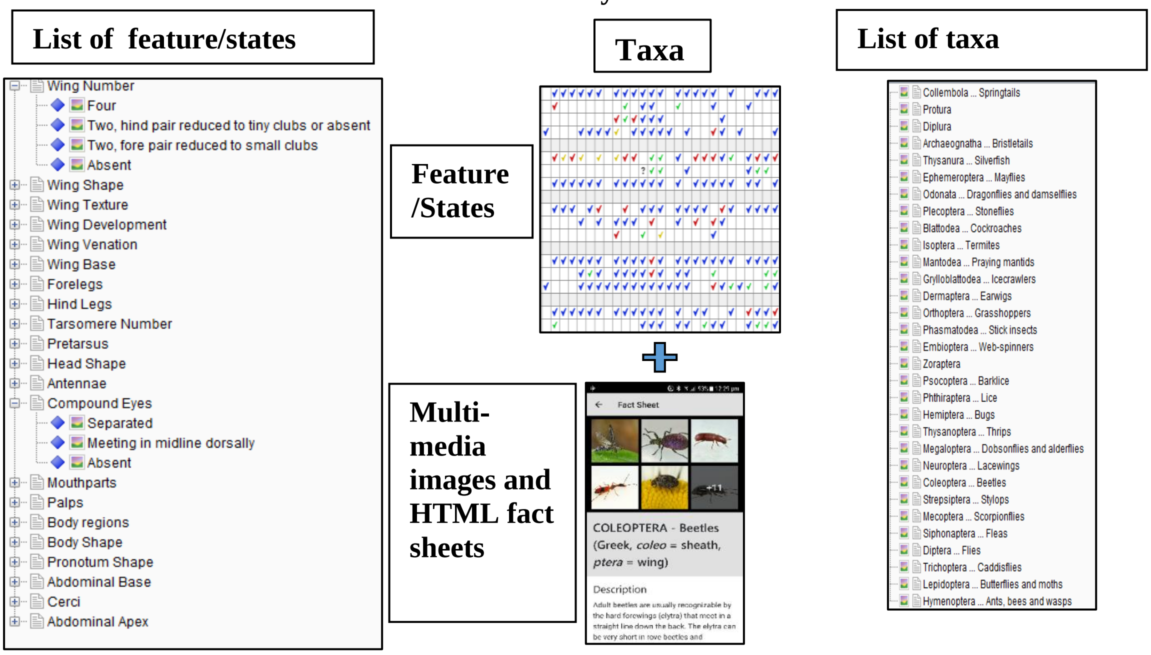
For more complex dichotomous keys, software initially developed for matrix keys (see next section) has recently been modified to allow the construction of digital dichotomous keys. More importantly, it allows existing published (hard copy) dichotomous keys to be imported via builder software, checked for inconsistencies, and incorporated in an online player. For example, a series of keys to insects and spiders found in rice in Southeast Asia and West Africa, initially published in books over 20 years ago, have now been incorporated in the software and are freely available online at **IAPPS**.

2.4. Matrix keys

Novel software developed during the ICT revolution, initially in the 1970s and 80s, provided the opportunity for different matrix-based identification tools to be developed. One of the earliest matrix key programs was the **DELTA System**, developed during the 1980s at CSIRO in Australia. Two other systems were developed in the 1990s, the **Lucid system**, initially developed at The University of Queensland, and the **Linnaeus identification system**, developed at the University of Amsterdam, and now incorporated in Linnaeus NG.

To build a matrix key to insect orders, **as shown in the diagram below**, information about the two axes, i.e., the list of taxa and the list of morphological features (feature/states) important for making an identification, need to be entered in the matrix. The cells in the matrix (denoting a feature/state for a specific insect order) are scored for presence/absence, common/ rare, or misinterpretation (where users are likely to select a feature/state by mistake).

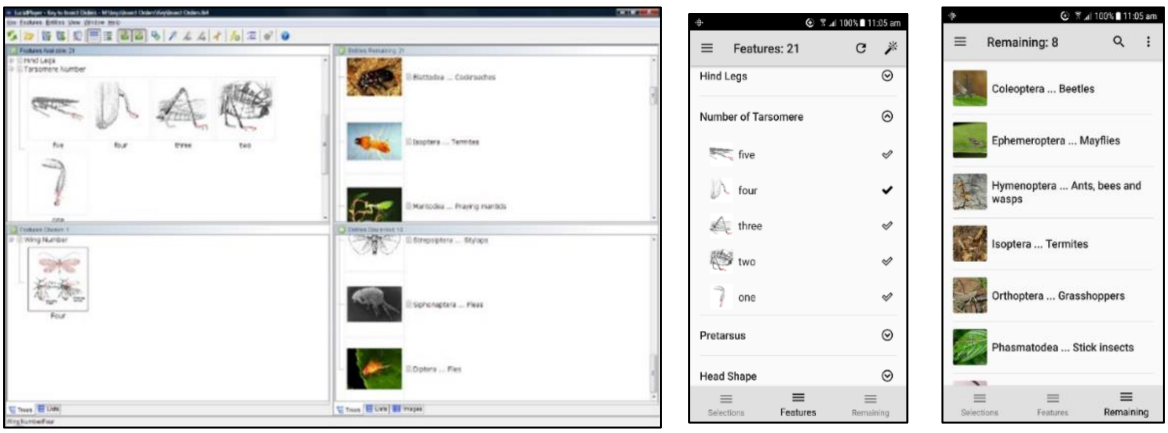
A matrix key for insect orders



Once the data has been incorporated and scored in the key builder, images and supporting text can be linked to the key's feature/states and taxa, helping users make an identification. When a key is completed, it can be deployed as a DVD, USB, online, or as a mobile app, depending on the builder platform used. The **screen shots below** show the insect order key displayed in two different player formats: (a) the 4-window format for an internet or desk-top player, showing *Features available/selected; Taxa remaining/discarded;* (b) the single screen format for smartphones/tablets.

Two player options for the key to insect orders

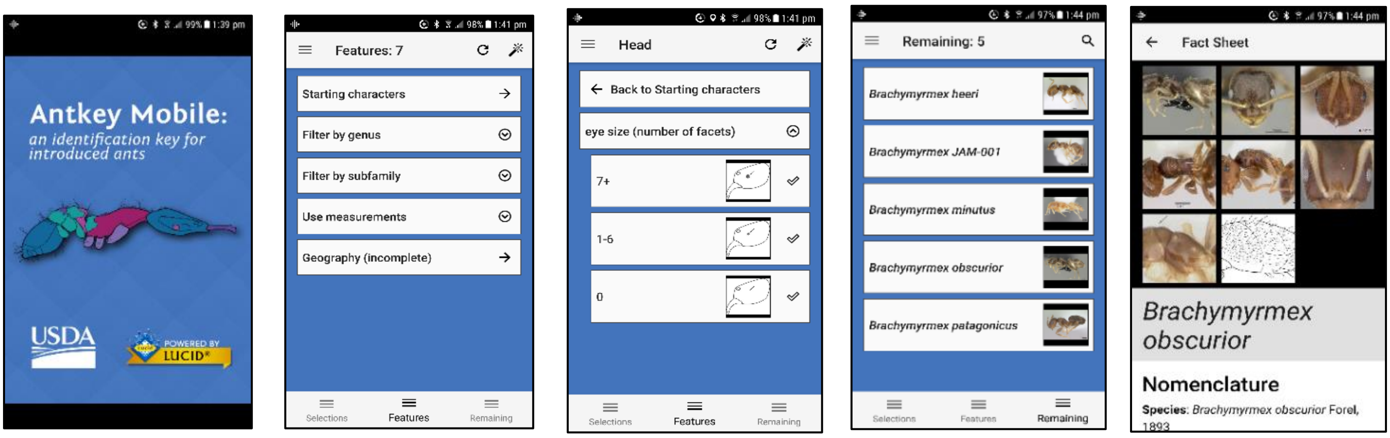
(a) Internet/desktop player format **(b) Mobile player format**



For the mobile app format, the *Features* screen shows relevant feature/states. At any time, the *Entities remaining* screen can be accessed by swiping left or via the options shown at the bottom of the mobile screen.

The mobile app '**Antkey Mobile**', **shown below**, is a community resource that includes an online matrix key to help identify invasive and commonly intercepted ant species from across the globe. Available as **Apple** and **Android** versions, the apps enable the full key to be used anywhere, without requiring access to Wi-Fi or a phone connection.

Screen shots taken from the Antkey Mobile App



Matrix keys have also been used to provide diagnostic tools that help growers, crop advisors, and surveillance teams diagnose observed symptoms in crops, which may have national or regional biosecurity implications.

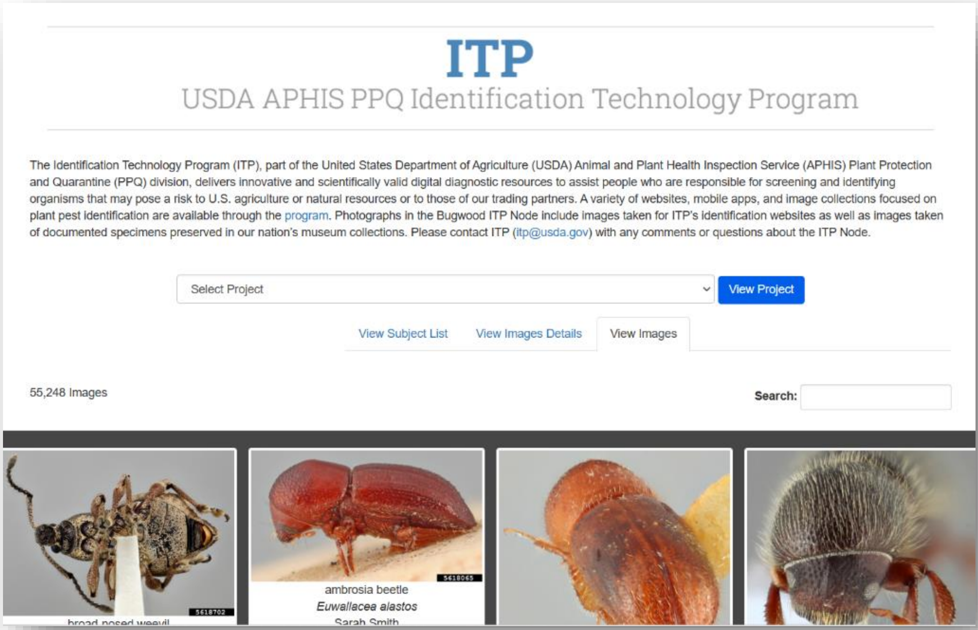
2.5. Image galleries/databases

Many online image galleries and databases have been created specifically to help identify certain groups of pest insects, beneficial insects, diseases, etc., or to provide a gallery of pests and diseases associated with a specific crop or commodity, such as you would find in a hard copy field guide for a specific crop. The number of databases that are specifically relevant to biosecurity concerns are much more limited.

In the USA, the **Center for Invasive Species and Ecosystem Health,** based at the University of Georgia, is a collaborative project that allows users to search detailed images of invasive and exotic species of plants, insects, and diseases, **as shown in the screen shot.**

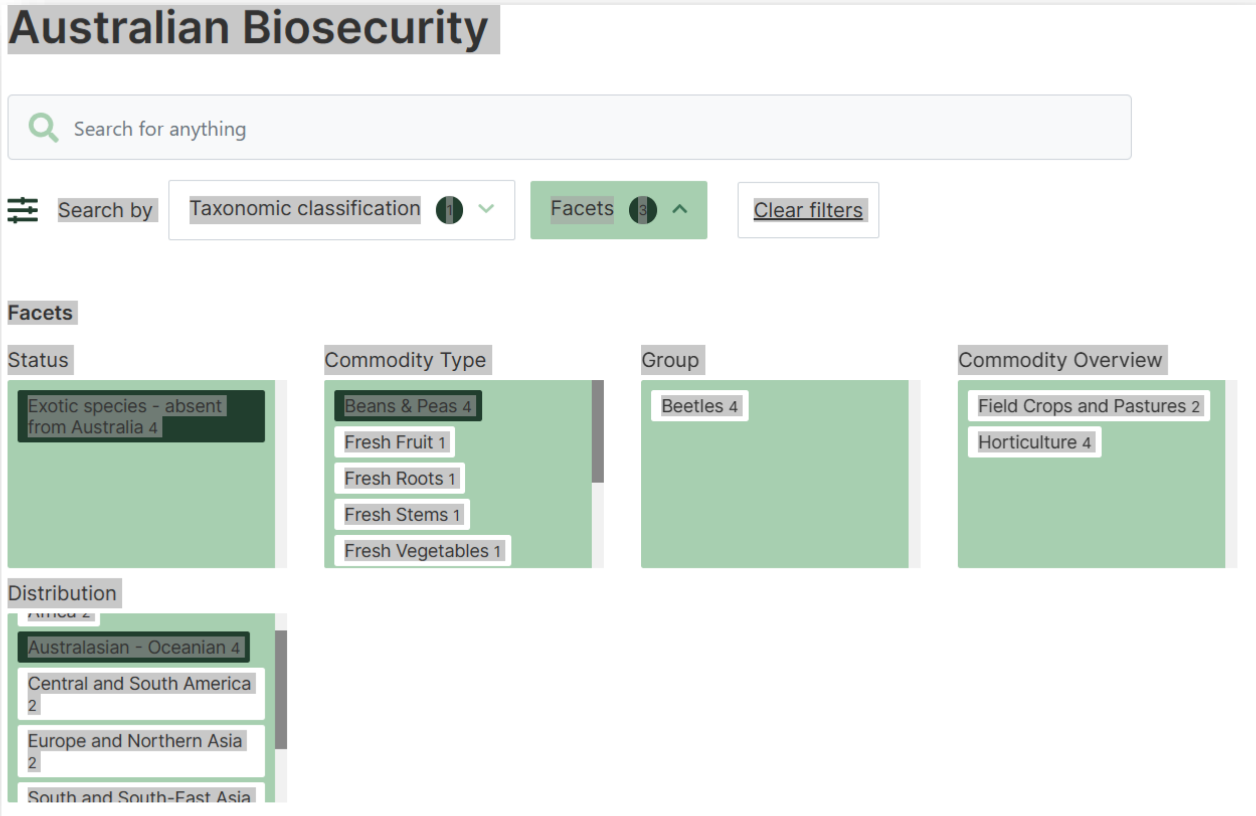
Apart from images, this site also provides a range of other support material, including invasive species databases, pest detection, etc. The major purpose of this database is to provide images to various government departments and NGOs for outreach programs and for reuse in field guides, outreach websites, educational materials, *etc*.

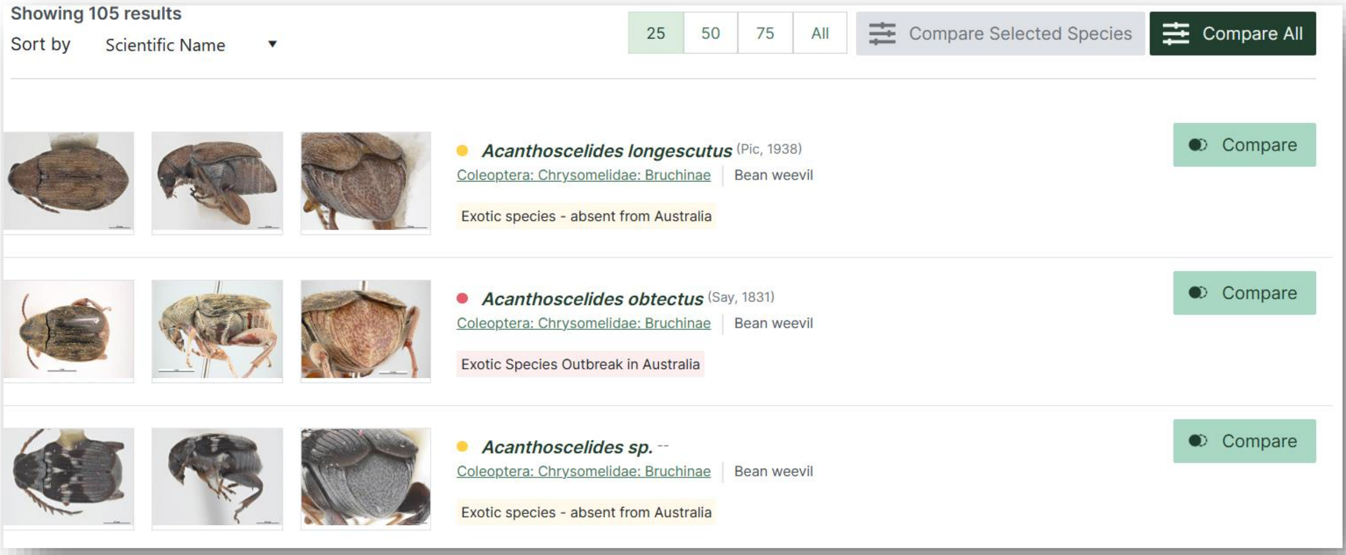
A specific node associated with this database has been developed through collaboration with the USDA's ITP. Images that are taken for use in specific ITP projects (such as providing illustrations for fact sheets in identification keys or for pest screening aids) are contributed to this node and available to other users, **as shown in this screen shot**. As these images are frequently of type specimens and the information from the museum holding the specimen has been added, these images provide a higher level of confidence to users that the identification is correct.



Through this collaboration, ITP also developed a similar database specifically for federal pest identifiers at ports-of-entry. This secured system includes everything from the ITP Node, but it also includes thousands of images of intercepted pests taken by identifiers. This allows identifiers to quickly and easily compare an unknown intercepted pest with validated images to help expedite the movement of cargo when regulated pests are found.

In Australia, a biosecurity-focussed image library (PaDIL) has been developed - the **Pest and Disease Image Library** Hosted by Plant Health Australia, this image library focuses on pest organisms of particular concern to Australian agriculture. A search function allows users to view images of major insect pest groups, plant diseases, and weed seeds [**see screen shots below**].





In New Zealand, a diagnostic image database website – PHELdi – is being developed by New Zealand Plant Health & Environment Laboratory for supporting biosecurity officers of Pacific Island countries in pest diagnosis. Species records (with downloadable fact sheets) for more than 600 insects of biosecurity importance to New Zealand and the Pacific have been prepared, peer-reviewed, and uploaded into PHELdi.

Once the PHELdi database has been published online, these records will be available to the public through the external **MPI Biosecurity webpage**. It is anticipated that PHELdi will provide a stable and easily accessible repository of scientifically accurate species descriptions that will help biosecurity staff in the Pacific to identify plant pests. The database itself will continue to grow as more records are added and updated by MPI staff.

In addition to these broader image libraries (covering a range of organisms of importance to biosecurity) other important image databases focus on specific taxonomic groups. For instance, the **AntWeb image database** covers over 16,000 valid species of ants.

2.6. New technologies including AI

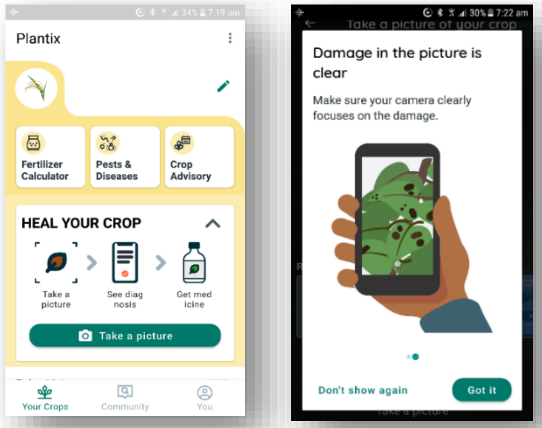
The success achieved in the development of image recognition software for facial recognition and for diagnosing melanomas and other skin disorders, has resulted in several applications of machine deep-learning to the identification and diagnosis of “pests”.

An example of an AI development for a specific biosecurity issue is provided by the Ministry of Primary Industries in New Zealand, who have developed a prototype for the identification of the brown marmorated stink bug, a pest at high risk of being introduced to New Zealand. Intended for use by citizen scientists, the aim is to achieve rapid identification of this important invasive pest in the event if breaches the New Zealand border.

Another prototype app, for the identification of weed seeds, uses the camera on a smartphone **Schmidt-Lebuhn et al. (2020)**. This app provides the user with estimates of confidence in an identification, species profiles, and thumbnail images.

Other examples of AI applications to plant pests have been concerned with the diagnosis of general pest problems or diagnosing specific crop diseases. **Plantix** is a mobile crop advisory app for farmers, extension workers, and gardeners.

Plantix provides diagnostic services on pest damage, plant diseases, and nutrient deficiencies affecting a wide range of crops and suggests suitable treatment measures. Plantix currently combines the results of AI diagnostic technology with support from an online community of scientists, farmers, and plant experts. Plantix will modify its modus operandi when the accuracy of the AI improves with more images being analysed.



Another crop diagnostic app that uses AI technology, and which also has a back-up expert community to respond to diagnostic requests, has been developed by the **PlantVillage** community plant protection support team at Penn State University. Called "Nuru", this app was created as an AI assistant for small holder farmers in Africa, with three AI components: 1. human expert-level crop disease diagnostics based on computer vision; 2. use of ground and satellite derived data to improve diagnosis; and 3. use of language comprehension and automated responses to farmers' questions.

In China, there are several examples of AI platforms being used to provide plant protection support. **Love Plant Protection** is an artificial intelligence platform for plant protection developed at Zhejiang University. It supports online intelligent identification of agroforestry diseases, insect pests, and weeds; remote control guidance; data analysis; and an agricultural information service. App users can take pictures on-site and accurately identify more than 600 kinds of agroforestry diseases, pests, and weeds, and more than 200 plants online. Users can access reference information and obtain remote technical guidance from experts. The information provided by users can yield information about the real-time occurrence and spread of agricultural and forestry diseases, pests, and weeds in specific areas.

Another AI diagnostic app developed in China uses the social communication platform WeChat. Developed by a scientific company in Beijing, users can photograph disease symptoms on seven specific crops (currently) and upload these images to the AI cloud. In return, they receive information about the disease causing the symptoms, the confidence level of this diagnosis, and fact sheets about the disease with management options.

A project for diagnosing pests and diseases of banana using AI technology has been reported by the **International Centre for Tropical Agriculture** (CIAT). In this case, the plan is to use deep convolutional neural networks (DCNN) and transfer learning to develop an AI-based banana disease and pest detection system to support banana farmers.

Typically, the development of image-based identification tools employing AI requires large numbers of images, often of sub-optimal or non-standard views. All tools of this type are challenged by the existence of large numbers of or poorly characterised 'background' taxa and by cryptic or visually very similar species.

2.7. Searching for DITs for biosecurity

Since generic online search engines often return results that may not be particularly useful or accurate, ITP has created a database for quickly finding reliable web-based, identification-related biosecurity resources, including (but not limited to) fact sheets, interactive keys, screening aids, and image galleries. ITP's dedicated staff curate a collection of vetted "IDaids", including over 6057 resources (as of April 2023), and this continues to grow. **Search IDaids** allows you to search for relevant tools by pest name (common or scientific) at any taxonomic level, and then refine a search by tags including geography, commodity, or resource type. This platform illustrates the potential for DITs to provide an accessible, virtual community for data collaboration and knowledge sharing.

3. Four case studies of the development and use of DITs for biosecurity

Introduction

Important practical issues face organisations responsible for developing DITs for biosecurity agencies: deciding which biosecurity issues would most benefit from a DIT; what expertise will be required; and how it will be funded? To explore these issues, we first examine two biosecurity agencies, both of which have considerable experience in this area, one in the USA and one in Europe. We then focus on the role that international collaboration can play by referring to case studies that illustrate how sharing tools and data can contribute to the number of DITs for two different, important pest categories – thrips and weed seeds.

3.1. The USDA Identification Technology Program

ITP supports USDA APHIS Plant Protection and Quarantine (PPQ) in its mission "to safeguard U.S. agriculture and natural resources against the entry, establishment, and spread of economically and environmentally significant pests and facilitate the safe trade of agricultural products". It strives to keep PPQ's digital identification resources current through the delivery of a variety of innovative, scientifically valid, digital diagnostic resources to individuals responsible for screening and identifying taxa that pose a risk to U.S. agriculture and natural resources, and to U.S. trading partners. ITP develops these diagnostic resources by collaborating with taxonomic experts from around the country and the world and providing training and technical support for the development of quality products. As of the end of 2022, the number of DIT resources developed by the ITP team are summarised in the table below.

Summary table: numbers of keys, diagnostic aids, fact sheets, images, and more developed through ITP.

Keys	72
Screening aids for state surveys (pdf)	44
Identification tool (ID tool) websites	47
Fact sheets	5320
Images	Over 55,000
Mobile apps	15+

During 15 years' experience developing DITs, ITP staff have developed a 5-step checklist, described below. It aims to ensure the DIT is relevant to biosecurity decision makers and is achieved cost-effectively.

The ITP DIT development process

Stage 1 – Identify the problem and audience.

Several decisions should be made early in the process, having determined the pest group for which a DIT appears appropriate. First, is the taxonomy of the group in question resolved, or does it need work? If the taxonomy of the group is well-defined, the project may only require a literature search, and may be achievable with relatively few resources. However, if the taxonomy of the group in question requires extensive study, consideration needs to be given to breaking down the project into stages to allow the time required to resolve these taxonomic issues.

Project staff should identify potential funding sources early in the planning process. Government funding sources may be limited or may be based on prioritized pest lists, recent detections, or the type of product delivery. An awareness of funding sources early in the process is important; it may significantly impact the project's scope or coverage.

Clearly defining the biosecurity problem and identifying the intended audience is critical. Is a screening tool or a verification tool required? Is it for seasonal technicians, or highly educated professionals? Is the tool for use offshore, at point of entry, for industry, or domestic use? Each user group will have different requirements for content and delivery. Clearly defining the goal of the tool, or the problem the tool is trying to solve (and for whom), will help to focus on what will be needed to deliver a resource that will help solve the problem. Defining the scope of the tool involves not only the taxonomic coverage, but also the target audience.

Stage 2 – Determine the delivery format and features required.

Digital tools can be delivered in several ways, including interactive websites, downloadable pdfs, and mobile applications, depending on the needs of the targeted user(s). Field-focused resources might require a more portable format, while lab-focused tools may not. Content will also be dictated by the need being addressed. Screening tools make different content or support available compared with verification tools. For example, tools that that require compound microscopes or molecular methods to help identify specific pests are probably best delivered as a website. Resources for use in field surveys might be best deployed as mobile phone applications that can be used on handheld devices in areas where internet access is unavailable.

The taxonomic needs of the audience may also require different features, such as an interactive gallery, a true identification key, or video tutorials.

Stage 3 – Scope relevant experience required.

With the taxonomic coverage, target audience, and tool delivery defined, the next task is to scope the relevant experience required to complete the tool. Specialists in the target group may be needed to help create the content, and potential users should be recruited for testing, since tool users will generally not be specialists in the group covered by the tool. Technical web or app development support may also be necessary. Consideration of how to keep the resource up-to-date will be needed as technical support needs are identified.

Setting boundaries for resource coverage and scope (and sticking to them), is essential for timely delivery of a useful identification resource. When feasible, ITP tries to limit the entity list to 100 to be achievable in an annual funding cycle. Mitigating circumstances include the amount of taxonomic work, imaging, and molecular work that a tool will require. For instance, many of the ITP web-based or mobile app products include an interactive key, fact sheets, images, and additional supporting content. Including all these elements for a numerically large pest group often requires more work than realized, much of which is tedious and time-consuming. It is crucial to find a way to break large projects into manageable parts to be developed and completed over several years.

Stage 4 - Form a development team, create a work plan and timetable, and confirm funding.

An effective project must have staff specifically dedicated to each task in the project. Project staff must create a detailed work plan with goals and due dates, and then follow that plan.

Stage 5 - Manage process, product testing, release, monitor and update as needed.

A project manager, or a precise schedule, helps ensure all the tasks and objectives of the project are completed in a timely manner.

Beta testing is important to verify the accuracy of the content and the usefulness of the tool for its intended audience.

Many staff and interested individuals have an expectation for websites to be up-to-date compared with paper-based resources. Thus, it is also important to incorporate a schedule for updating in the project plan.

The 5-stage process described above has helped ITP successfully develop many individual digital identification products, aimed to address specific needs over the last 15 years. With this process in place, ITP has more recently shifted focus toward improving the systems behind the products. For instance, as mentioned earlier, ITP developed Fact Sheet Manager, an online content management system, based largely on Fact Sheet Fusion, to provide ITP's digital tool authors with an easy way to upload their fact sheet data to an online relational database. That database is connected directly to the front-end website for the identification tool users, which allows for real-time updates.

Fact Sheet Manager not only allows authors to collaborate over long distances; it also enables them to update their fact sheets more easily, without needing to understand how to edit a web page. Having all the fact sheet data in one place also offers flexibility for the future; with greater access to trusted data, future identification tool builders can easily grab that data to repurpose it for their own identification products.

A fully integrated online system that supports the development of high-quality identification resources, from start to finish, helps to streamline some of the most time-consuming and challenging parts of digital identification tool development. ITP continues to focus on products that allow users to upload new data or reuse existing data to create identification aids to meet a wide variety of needs and then post them for linking and sharing with specific audiences.

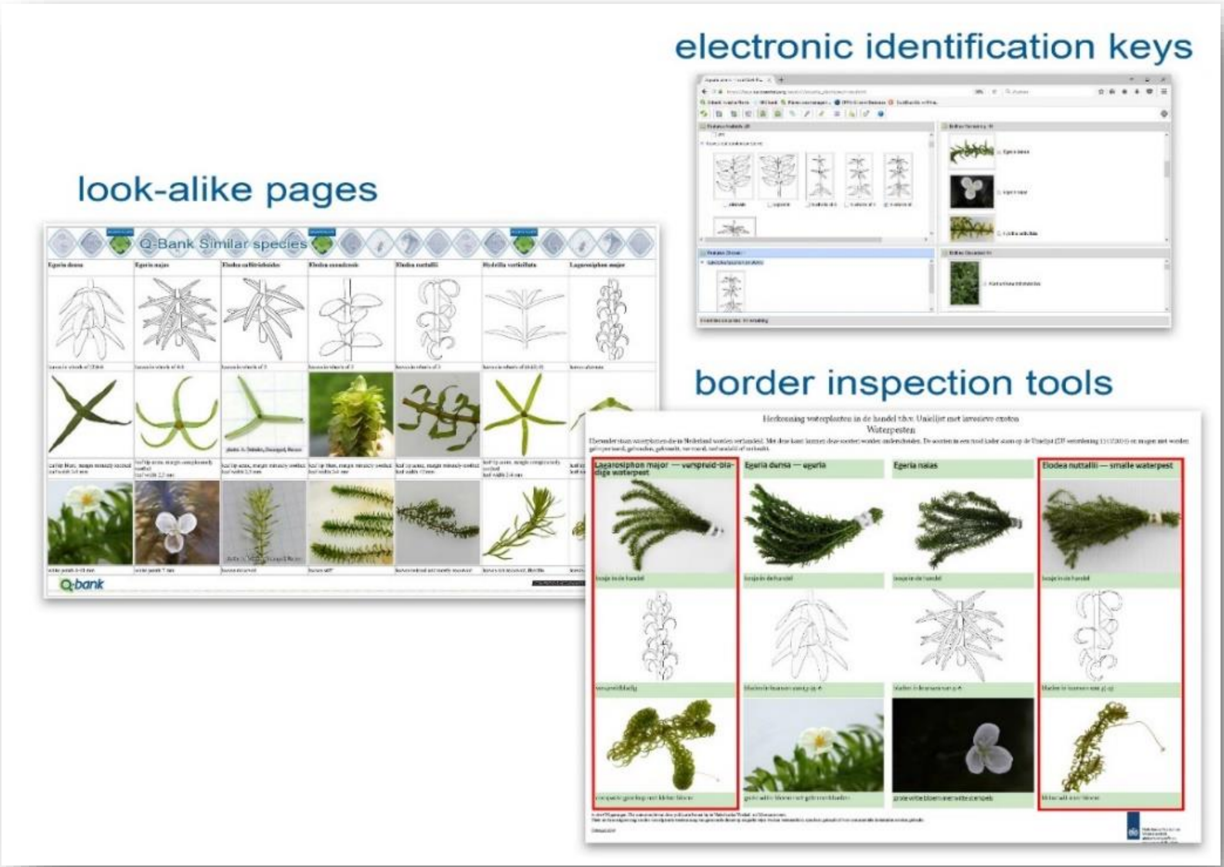
As some of the stumbling blocks for developing online identification tools are addressed, resources become more available to focus on supporting integration of existing DITs with those produced by other organizations. This includes increased standardization of image quality and techniques, identification of key features and states, and fact sheet topic content fields.

3.2. Q-bank invasive plants and EPPO-Q-bank: identification tools for biosecurity

Q-bank invasive plants was initially developed in 2007 as an information system for (potentially) invasive plants for the Netherlands. As a result of an EU-funded transnational project on invasive species (RINSE, EUPHRESCO DeCLAIM), the scope has widened to cover the northwestern European Atlantic zone.

In 2019, **Q-bank Invasive Plants** was split into a section containing molecular information and related specimens, managed by the European and Mediterranean Plant Protection Organization **EPPO**, while the remainder involving species and specimen information, fact sheets, border inspection tools, and look-alike pages, is now managed by the National Plant Protection Organization of the Netherlands.

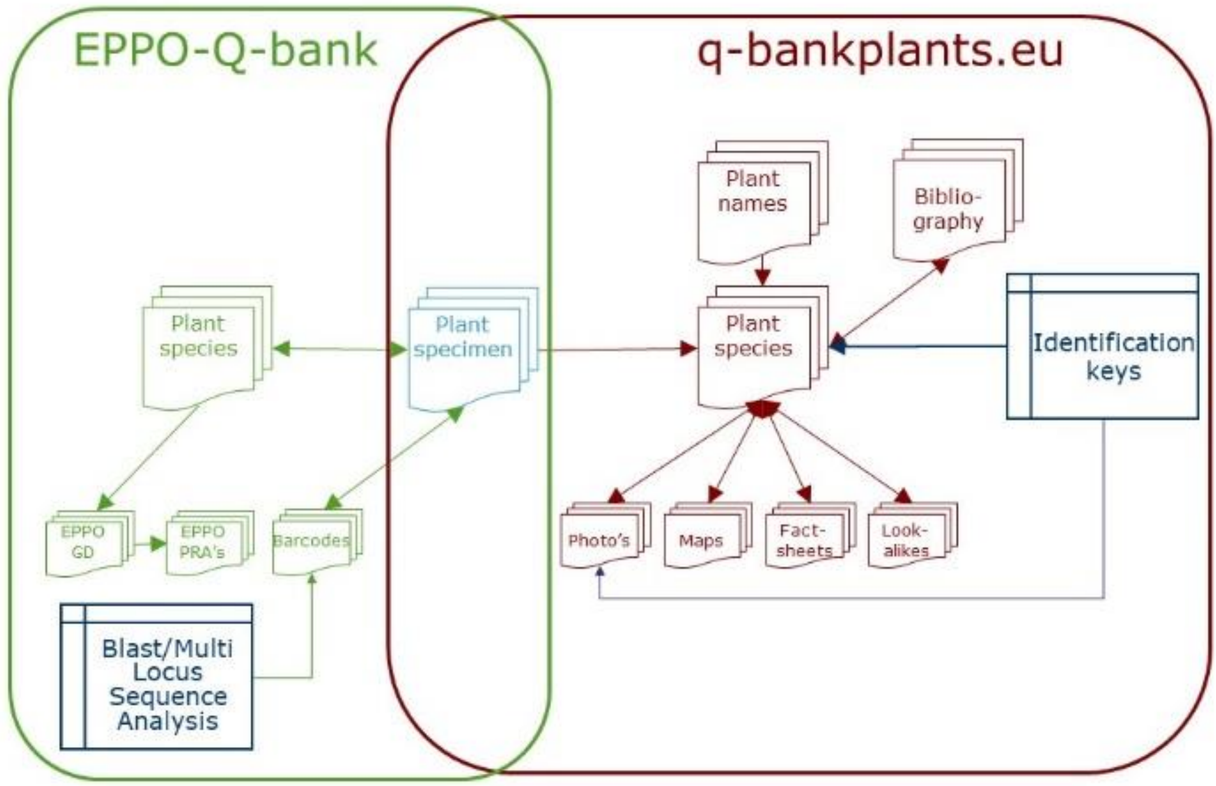
The invasive plants module provides detailed species-level information on invasive alien plants with a focus on contaminants in import shipments, including all plant species on the European Union (EU) list of Union concern, associated with EU regulation 1143/2014. This includes fact sheets, look-alike pages, and border inspection tools to facilitate identification during border inspection and verification of interceptions in support of the implementation of the EU regulation regarding invasive alien species. Moreover, links are provided to the interactive identification keys - **see screen shot.**



The first interactive key built for Q-bank dealt with weed contaminants of potted plants imported into Europe. Some of these weeds show invasive behaviour, and proper identification is essential to track accidental introductions rapidly. Identification of weeds in potted plants proved to be difficult because floras (the commonly used identification tools) generally only cover a limited geographical area. Moreover, "traditional" floras seldom include non-native weedy plants. The weeds to be identified originate from many different countries and continents and even include cultivated plants. This means that identification of these weed species using floras is falling short and, for that reason, an inspection tool for identification of these plants had to be developed.

The first species included in a key were based on an inventory of weeds found in bonsai plants imported from China. At a later stage, more species were added as they were intercepted in potted plants imported from other production regions of the world. Currently the key covers 143 species. The way different species have been scored for the different characters can be viewed and assessed by users.

The species in the keys are all illustrated by photographs showing the distinguishing characters; a link to species information on Q-bank invasive plants is also provided in the keys. Here users can find more information on the species, a selection of herbarium voucher specimens, as well as a link to molecular data in EPPO-Q-bank. The links between the different databases on invasive plants within Q-bank invasive plants and the interaction with EPPO-Q-bank are **shown in the diagram below.**



The keys on invasive plant species currently available are:

- Weeds in imported potted plants in Europe
- Invasive terrestrial plants in Europe
- Invasive aquatic plants
- Seedlings of invasive plants
- Seeds of invasive plants
- *Pennisetum* cultivars

EPPO-Q-bank holds the molecular information (barcodes) of invasive plants. All sequence data available are curated and linked to a specimen including information on the collections where it can be consulted. These specimens are also included in q-bankplants.eu, that also harbours over nine thousand collections (mostly without molecular data).

EPPO-Q-bank allows the user to "blast" their own sequence data to be able to compare it with the molecular information in the database. Multiple Locus Sequence Analysis (MLSA) is also possible to use two or more loci in a single blast. Results are presented in a tabular format, and results from a single blast can also be assessed in a phylogenetic tree.

The species are linked to the EPPO Global Database. The aim of the database is to provide all pest-specific information that has been produced or collected by EPPO. This includes taxonomic position, EPPO code, common names, geographical distribution (with a world map), host plants, categorization (quarantine status), pictures of plants, datasheets, pest risk analysis, and EPPO Standards. Articles of the EPPO Reporting Service, a free monthly newsletter can also be retrieved from the EPPO Global Database.

The two previous case studies of USDA ITP and EPPO/Q-Bank activities focussed on needs for DIT use by their respective biosecurity agencies that are appropriate for the issues arising from their regional and commercial trading situations. In both cases, DITs developed by these agencies are publicly available for other agencies and individuals to use. The next two case studies have a different rationale, which involves international collaborative projects to develop and share data and DITs for two specific groups of pest organisms – weed seeds and thrips.

3.3. International Seed Morphology Association: resource development for weed seed identification

Detachable plant parts capable of being disseminated for propagating, commonly a seed or fruit, hereafter referred to as seeds, are the primary method for plant propagation and, consequently, the agent for the long-distance spreading of invasive plants and weeds. International marketing of seeds, grains, or other agricultural goods, which may be contaminated with unwanted seeds, present a considerable quarantine risk. In this context, seed identification to determine the family, genus, and species of intercepted seeds is especially important for identifying species that have quarantine significance across regions and borders.

Two approaches can be used to reduce the risk of weed spread via international trade. For over a hundred years, seed companies have used screening practices that allow them to certify that the crop seeds they market have been inspected and are not contaminated with weed seeds. The second approach is to inspect agricultural and other commodities to determine if they contain weed seeds, in which case, the species involved need to be identified to determine the level of quarantine risk.

The process of seed identification based on morphological analysis faces considerable challenges. Apart from the global decline in taxonomic expertise, specimen references and supporting resources for identifying species from other countries and regions are often limited.

To address these issues, the International Seed Morphology Association (ISMA) organized an international collaborative project in 2017 to establish a digital platform with three key components: virtual publication of a *Seed Identification Guide*, an online learning portal, and a peer-support forum. AI would be a suitable application for a peer support portal in the next stage of the DIT development. ISMA has also implemented strategies to facilitate international collaboration in developing data, images, and information matrixes for seed identification. The aim is to ensure compatibility between authors who may have various language profiles, technical knowledge, and professional background.

- ***Seed Identification Guide:*** This digital publication contains peer-reviewed seed identification fact sheets, an image gallery, Lucid matrix identification keys, and a glossary of botanical terms. Each fact sheet of a plant species has a description of the morphological features and images of dispersal units, a morphological comparison with similar species, plant species distribution, and other biological features.

  The number of species, keys, and image gallery will be expanded or enriched routinely as more publications are received from authors around the world, with no limitation of volumes or editions.

- ***Online Learning Portal:*** This portal provides online training tools and resources to support seed identification. For example, analysts or inspectors can use seed identification quizzes to learn about the seed morphological features of different species or families. Recorded webinars and posters provide further information about seed identification across various species.

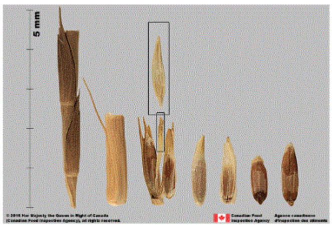
- ***Seed ID Forum*** – This forum provides a web-based virtual space where registered users can discuss or seek advice from their peers concerning botanical knowledge, seed identification, plant taxonomy, and nomenclature. In addition to the resources listed above, ISMA has also established a Publication Guide providing clear standards and guidelines for seed identification tool development to allow easy integration of products created by different groups.

Standardize data collection methods.
ISMA has developed a protocol for seed images and the size measurement for each seed description. ISMA also provides a standard template for authors to ensure completeness and compatibility, **as illustrated below.**

Example of seed image protocol for authors to facilitate the completeness of seed morphological information of each species:

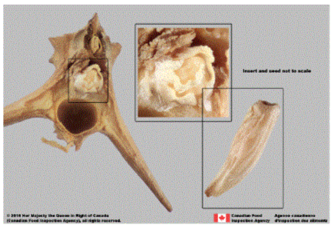
Image Type III: Image(s) of multiple forms of dispersal units and their associated parts: such as spikelet, floret or caryopsis for grass species and achene, seed, remnant floral parts, or bur for aster species.

- The image of the various forms of a dispersal unit in a species is to document the complete seed morphology information. For example, *Aegilops cylindrica* (*Poaceae*) rachis segments, spikelets, florets, and caryopses.



- The imaging of floral parts occurs when they are the dispersal unit or connected to seed or fruit features. For example, *Rumex crispus* (*Polygonaceae*) perianth and achenes.

- A cross-section or a longitudinal section of the dispersal unit may be useful to show the internal structure of the unit, and where the seed(s) are situated. For example, the internal structure of a *Tribulus terrestris* (*Zygophyllaceae*) disseminule.

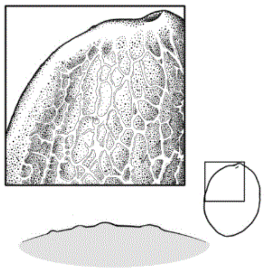


Standardize the feature descriptions.
ISMA has published standardized charts to increase the consistency of the morphological feature descriptions and their interpretation. Authors can use these charts to assist their writing, and the end-users can use them for their reference. There are charts for qualitative features (e.g., shape and colour description) and semi-quantitative features (e.g., surface texture description).

To illustrate, the following page includes examples of semi-quantitative features for raised or depressed decorations on seed or fruit surfaces.

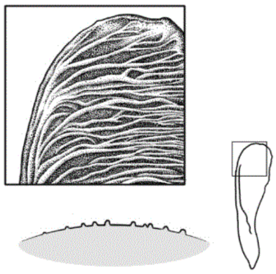
RAISED & GROOVED SURFACE DECORATIONS

Veins



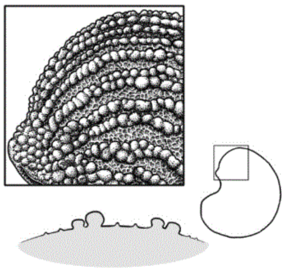
Lines that intersect in a vein pattern that is flush or slightly raised from the surface.

Nerves



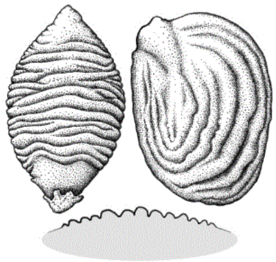
Raised, parallel thick lines or thin ridges on the surface.

Stripes



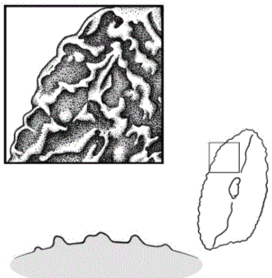
A series of linear surface decorations with the surface exposed between them.

Ridges

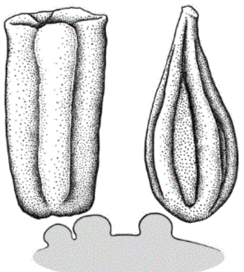


Raised, thick ridges, sharp edged or rounded, usually in a series that may cover the entire surface.

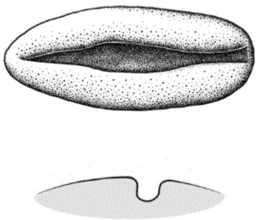
Irregular ridges



Ribs



Grooves

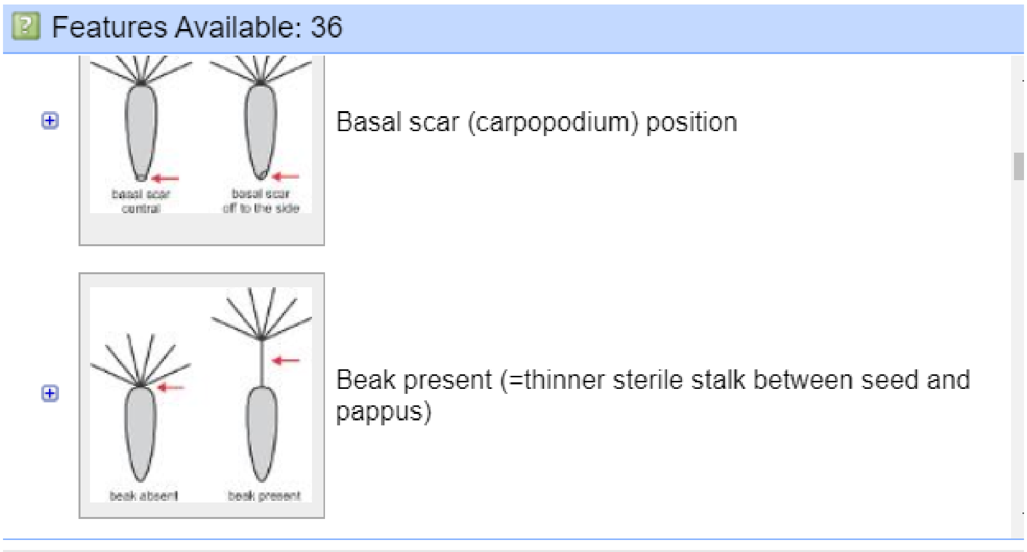


Cavities

Assistance for feature description and usage with multimedia

Multimedia assistance is recommended in feature descriptions, such as images and drawings for fact sheets, glossaries, and identification key state descriptions. Photos and illustrations with proper labels can help add precision and clarity to the feature description, as indicated below.

Illustration-aided state descriptions in a Lucid key.



*Notes: Credits to *Key to propagules of selected weedy Asteraceae (daisy or sunflower family)*, Alexander Schmidt, Department of Agriculture and Water Resources, the Government of Australia.

3.4. International collaboration on thrips key development

Over the past two decades, two prominent thrips taxonomists (Laurence Mound in Australia and Gerald Moritz in Germany), together with other international colleagues, have authored several thrips digital identification keys, often including related molecular tools and information. The first, a CD product, for identifying thrips species likely to be intercepted by quarantine officials in Australia, was produced in 1998. This led to further keys, including "Pest Thrips of the World" and a series of regional tools for use in North America, California, East Africa, the British Isles, China, and most recently, in Timor-Leste.

Early on, the keys were made available to users as CD-ROM products. Subsequently these keys have been updated and re-deployed as online keys and/or as Android/Apple smartphone apps. Over time, the authors have also added several features to provide additional information and training material for learning about thrips biology, classification, collecting, and microscope slide preparation. To enhance the tools for identifying thrips, photomicrographs and links to molecular techniques and data have been included. Brief details about these keys are provided below.

A brief history of the development and deployment of digital thrips keys (1998 – 2020)

Title of key	Authors	Online version	No. of taxa	Other components
AQIS Identification guide – Thysanoptera. Species most likely to be taken on plant material imported into Australia.	Moritz, GL. & Mound, LA. (1998) CD-Version – No longer available. Converted to online version	***Link***	80 spp.	Specimen preparation, Further reading, References
Thrips ID- Pest Thrips of the world	Mound, LA., Morris, D, Moritz, GL. (2001) CD Version	Not available	180 pest species, and all nine families	
Pest Thrips of the World: An identification and information system using molecular and microscopic methods	Moritz G.L, Mound LA, Morris DC, Goldarazena A. (2004) CD Version - English, German, Spanish Available online	**Link**	99 species	Sections covering Techniques, Tospovirus vectors, Glossary, Molecular key
Thrips of California (2008)	Hoddle MS, Mound LA, Paris DL (2008) CD-Updated 2012 and July 2019 Available online	**Link**	249 species	Browse species; Glossaries; Key references; Bibliography
Pest Thrips of North America (2009) - associated with domestic and imported crops.	Moritz G,L, O´Donnell C., Parrella, M. Available online	**Link**	91 species	Techniques, Thrips morphology, Thrips and Tospovirus, Crop introductions
Pest Thrips of East Africa (2013) -Identification and information tools for pest thrips of East Africa (family and subfamily key)	Moritz G, Brandt S, Triapitsyn S, Subramanian S CD Version (2013) Available online	**Link**	104 species	Key introduction, Slide preparation, Thrips Biology, Thrips natural enemies (key), Glossary, Library
Thysanoptera Australiensis 2020 An identification and information system to thrips in Australia	Mound LA & Tree DJ (2020) *Thysanoptera Australiensis* – Thrips of Australia. Lucidcentral.org, Identic Pty Ltd, Queensland, Australia. [Revised version of "Ozthrips" (Mound *et al*., 2012]. Available online	**Link**	340 species in 5 Families of the Sub-Order Terebrantia 140 genera in sub-Families of the sub-Order Tubulifera.	
Thrips of the British Isles (2020)	Laurence Mound, Dom Collins, Anne Hastings. Available online	**Link**	177 species of thrips taken alive on the British Isles at least once	Introduction to what is known of the biology and distribution of each species
Thripidae genera from China	Zhang, Shimeng; Mound, LA; Hastings, A. [English, Mandarin] Available online	**Link**	98 genera of the Thysanoptera family Thripidae	Prepared as part of Shimeng Zhang's PhD degree Northwest A & F University, China
Pest thrips in Timor Leste (2019)	Mound LA (2019). English; Bahasa Indonesia; Lingua Portuguesa Available online	**Link**	48 species	Aim is to identify pest thrips and distinguish them from the many thrips species likely to live in Timor Leste.

4. Issues to be addressed regarding the future of DITs for biosecurity and plant protection

Until the end of the last century, if a biosecurity official intercepted an organism which could possibly be a quarantine risk, he or she had two options for identifying it: sending the specimen to a relevant taxonomic specialist or using published images or dichotomous keys to make an identification on their own.

The explosion of digital hardware and software technology during the past 30 years has potentially transformed the situation. A range of digital identification tools have been developed which, when published online and as mobile apps, provides the potential for biosecurity officials and others to identify potentially invasive pests themselves. At the same time, rapid biotechnology developments have resulted in a range of laboratory and field-based molecular diagnostic techniques, providing additional tools for pest identification. The development of AI software focussed on image recognition presents new opportunities for on-the-spot identification.

Clearly, these developments provide new opportunities to support pest identification by quarantine staff and other plant protection decision makers. However, how accurate, appropriate, resilient, and sustainable future digital identification tools will be depends on the context in which they are developed and funded, and the way in which they are implemented. These issues are addressed in this final section of the review, under the following headings:

- **Are specific DITs fit for purpose given a range of users and situations?**
- **Integration of DIT's with alternative diagnostic tools and other support systems**
- **Strategies for efficient and sustainable DIT development and deployment**
- **The future of digital pest identification**

4.1. Are specific DITs fit for purpose given a range of users and situations?

Digital identification tools developed for biosecurity purposes aim to provide support to a range of users – from entomologists, plant pathologists, and weed scientists, to experienced quarantine officers, testing laboratories, farmers, crop advisors, land care groups, and citizen scientists. The speed and specificity required of identification tools will depend on many factors, including the speed and precision required for operational purposes and the appropriate level of detail required. For example, identification of a *Trogoderma* species detected, in a warehouse containing imported and locally sourced goods, would probably need a definitive answer within hours, while the identification of the contents of a fruit fly trap from a remote, little-visited, offshore island might not require such urgency.

In both of these examples, a digital tool would need to support challenging identification decisions, such as providing diagnostic images of dissected structures in the case of *Trogoderma*, or depicting variation in colour markings in the case of fruit flies. Less precise identification may suffice in other situations. For example, if a surveillance officer detects a leaf-mining caterpillar in an Australian tomato crop, an initial identification to genus-level only (which would reveal whether the caterpillar was the endemic *Phthorimaea operculella* or the exotic *Phthorimaea (formerly Tuta) absoluta*) might be sufficient for initial decision making.

In other cases, for instance where a digital key has been developed to identify snails, a relative novice may be able to perform an identification quickly and with confidence. For some situations, such as a digital tool developed for identifying certain insect species that requires the dissection of genitalia to make a positive identification, practical training will probably be required before the user could be regarded as proficient.

Where DITs are to be used for pest management in the field, they might need to include non-pest species, including beneficial insects (natural predators of pests and pollinators) and neutral species that pose no threat but may provide additional food for beneficial species. By contrast, tools developed for use at quarantine stations may require a very specific focus – that is, what pests may follow a particular pathway? This may include species that would not naturally be found in a particular commodity but may wind up there due to the unique circumstances that occur with worldwide shipping. Training tools may have yet another focus, as these tools may need to include more basic taxonomic or quarantine information to ensure they are usable for a less experienced audience.

Having the flexibility to deploy DITs online, as well as via mobile apps, can be critical in meeting the requirements of different users in different situations. Filterable image libraries and mobile apps, for example, may be useful for the officer undertaking field surveillance and needing to categorise a field observation, while online keys and molecular protocols and voucher sequences may be more appropriate for the laboratory technician who receives the surveillance officer's samples. DITs that include comprehensive information about taxa, such as detailed fact sheets and images, offer opportunities for online learning, particularly in association with distance training courses for improving the identification skills of inspection officers and technical specialists.

4.2. Integration of DIT's with alternative diagnostic tools and other support systems

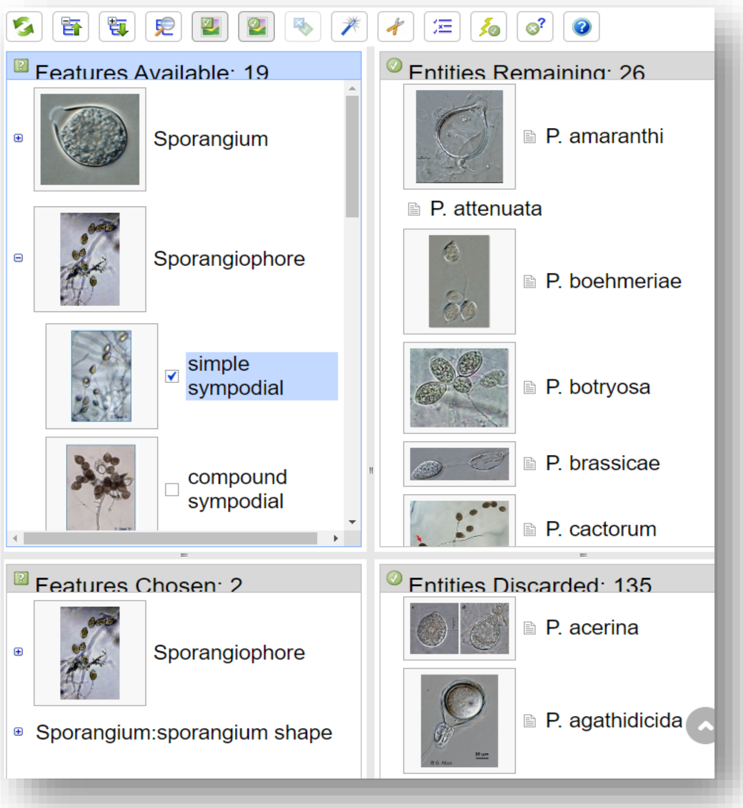
While a digital identification tool can provide an early and accurate result, using a different DIT device or an alternative identification technology, such as a molecular tool, may be necessary in some situations to provide confirmation of the result. Indeed, where feasible, combining different identification tools on the same platform is recommended. Earlier in this review various thrips DITs were described; in some cases, the thrips morphological identification key is supported with sections providing relevant molecular analysis techniques for the taxa involved.

A more recent example shows how a digital identification and diagnostic tool for ***Phytophthora* IDphy** brings together a series of different types of identification tool on the same platform. Developed by a large team of scientists over a period of 8 years, IDphy is one of the most comprehensive tools ITP has ever published, covering all the valid described species within the genus (as of 2022).

Released in 2019/20 as an online resource and subsequently as a mobile app, IDphy includes the following range of identification and support tools:

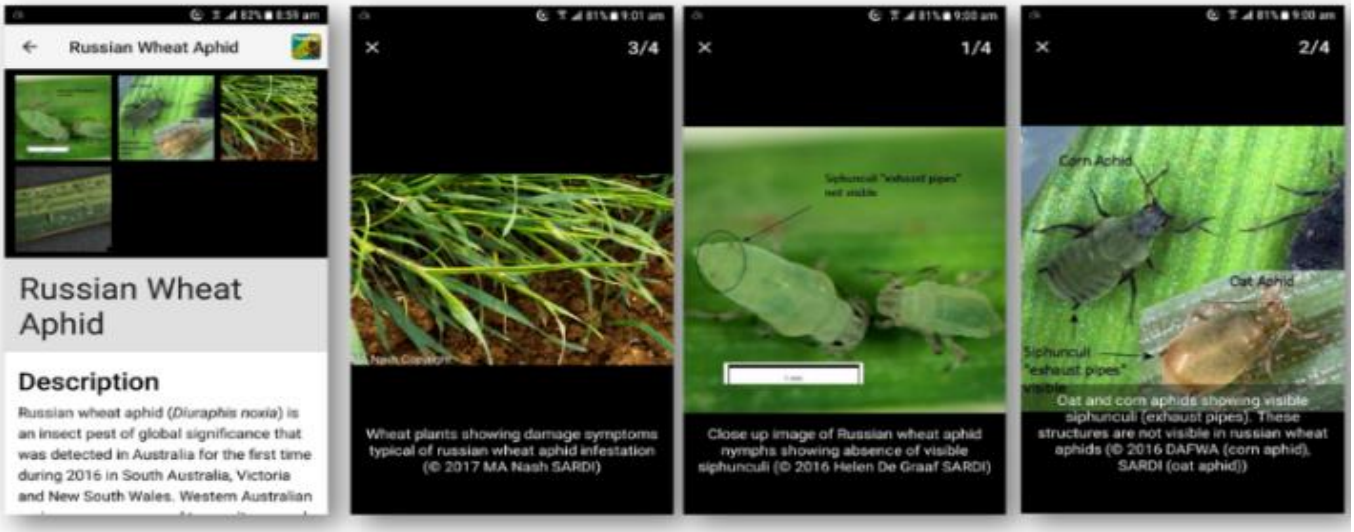
- Detailed protocols for molecular identification, including:
    - sequence vouchers for ITS rDNA and COI
    - protocols for SOPs for DNA extraction, PCR, electrophoresis gels, and sequence-based identification.
- Voucher sequences from the types, providing the most reliable source of reference material for the tool
- Filterable image gallery
- Morphological interactive Lucid key
- Searchable fact sheets
- Tabular key for quick reference
- Background and life cycle/biology information

Morphological identification of *Phytophthora* species – based on characters of asexual and sexual phases and colony morphology.



As well as combining DITs with other identification techniques, there are other opportunities to combine DITs with reporting, surveillance, and forecasting platforms. For instance, a diagnostic wheat app **Android**; **Apple** developed by the Western Australia Department of Agriculture, includes 86 insect pests, diseases, and other disorders. In 2016, when a new invasive pest, the Russian wheat aphid, was first detected in Western Australia, the diagnostic apps were rapidly updated to include details and images of the Russian wheat aphid in the key to help distinguish it from other aphid pests. If a farmer or consultant thinks they have detected and identified this introduced pest, they can report the details to authorities by clicking on the "Pestfax" icon at the top-right corner of the relevant fact sheet **- as shown below.**

Screen shots from the MyCrop Wheat app, Western Australia Department of Agriculture



A further example of how extra functions can be combined with ID tools is provided by the development of international "harmonised databases", such as that for cassava, a tool being developed by the International Centre for Tropical Agriculture **CIAT**. The aim is to create a coalition of platforms to make sure that wherever new incursions are detected, they are reported, and the data gets to the right people to provide a better overall picture for decision making. Therefore, the line between technical assistance with pest identification, diagnostics, remote diagnosis, and active monitoring has become blurred. The barrier between assisting with diagnostics and leveraging that information into a surveillance and monitoring platform has become more a matter of policy and politics than technology.

4.3. Strategies for efficient and sustainable DIT development and use

Several examples of DIT development and deployment, described earlier in this publication, indicate there are various ways in which efficient and sustainable development and use of DITs can be achieved. Some of the strategies for achieving this outcome are summarised below.

- ***Strategic development processes.*** In section 3 of this review, we discussed the processes developed by two government organisations for developing and implementing DIT tools: USDA ITP and EPPO/Q-Bank. The structured and comprehensive approach adopted by both organisations provides important lessons on how to design strategies that deliver efficient, sustainable, and effective digital identification support programs.

- ***Collaboration and sharing data and DITs.*** Two other case studies, described in section 3, have shown how international collaboration and the sharing of information, data, and DITs can also achieve more efficient and efficient DIT development. The collaborative projects that thrips taxonomists have engaged in for over 20 years has resulted in the development and sharing of a database of thrips identification data. This has enabled new thrips keys to be rapidly developed for use in specific regions, by combining thrips key data contained in the shared database with new information resulting from collaboration with local entomologists.

- Data sharing has also been achieved by developing platforms for both sharing and delivering DITs. The ISMA platform, described in section 3, provides a good example of the range of support that can be provided on various aspects associated with developing and using DITs for weed seed identification. Similarly, the invasive species image database project **Bugwood**, mentioned in section 2.5, involves another example of collaborative data sharing across many states in the USA as well as internationally, providing a valuable international source of images relevant for pest identification and crop diagnostics. Use of web services increases the ability to share data and allow third parties to bring together and use data in new and innovative ways.

- ***Utilising generic platforms and standards.*** Apart from collaborating on DIT development and the sharing of data, a more efficient development and deployment strategy for DITs can be achieved by utilising generic software platforms, rather than developing one-off, bespoke software. The development of three generic matrix key software platforms, described in section 2.4, has enabled many hundreds of taxonomists and other specialists to develop and deploy matrix keys on the internet and as mobile apps. Since constant upgrades and updates are required for developing and deploying DITs, especially when deployed as mobile apps, generic platforms provide a much more cost-effective way of achieving this.

Nevertheless, there are still important issues that must be addressed to sustain the viability of DIT software platforms. In the 1980s and 1990s, most land grant universities in the USA received funding to develop digital "expert systems" that provided decision support to a range of plant protection activities. In many cases, once the funding grants came to an end, and details of the expert system were published, there was no appropriate funding mechanism to support continued development and maintenance of the decision support tool.

This has also been an issue for some of the DITs mentioned in this review. Some have survived through long-term funding from biosecurity agencies. The group responsible for Lucid software products, who have been developing and supporting the development of DITs for over 25 years, initially received funding through a government-funded Cooperative Research Centre but subsequently had to develop a strategy involving:

A range of funding sources - *grants, contracts, software sales, non-Lucid contracts*.
Flexible R&D activity – *initially university-based and subsequently involving a spin-off company.*
Focus on generic software products – *Lucid Builder; Lucid Mobile platform (over 100 apps published).*
Close collaboration with authors – *website, forum, help desk, workshops, ideas for new software features.*

4.4. The future of digital pest identification

Before addressing specific opportunities and constraints regarding future development and use of DITs, it would be remiss to ignore the fact that recent development and use of DITs and other ID technologies has occurred at a time when there has been a dramatic reduction in the number of specialist taxonomists worldwide. Few universities now teach taxonomy, and it is not unusual for many developed and developing countries to lack taxonomists specialising on major pest taxa.

Since the precision of DITs in distinguishing specific pest species can make a critical difference to quarantine risks and the action taken, the importance of up-to-date taxonomic information about major pest species can be critical. Suffice to say that unless this taxonomic crisis is addressed, it could constitute an important constraint to the future development and effectiveness of authentic DITs.

As already discussed in this final section, there are several issues that require more attention to ensure future DIT developments to support plant biosecurity decision making are efficient and effective, including:

- Improving feedback on the use and value of DITs to practitioners.

- Integrating different DITs with other identification technologies, such as molecular analysis, to provide a range of tools for different identification needs, enabling identification checks using different methods, and linking these identification tools to other surveillance and reporting platforms to provide agencies with comprehensive information systems. **Valkenburg et al. (2023)** describe a situation where both morphological and molecular techniques are required to distinguish certain *Salvinia* aquatic weed species.

- Adopting strategic approaches rather than ad hoc developments, encouraging increased collaboration and data sharing in the development and use of DITs, and using generic software platforms where appropriate.

The continuing development of computer and mobile hardware and software will undoubtedly enable the range of software tools described in this review to be further enhanced as new features become available. The recent success of AI software applications in other disciplines, notably for facial recognition and the diagnosis of skin diseases, such as melanoma, has stimulated interest in the use of AI for pest identification; some examples have already been described in Section 2.6.

However, three important factors have been responsible for the success of the AI applications to facial recognition and skin diseases: a relatively limited range of features that need to be analysed in a controlled environment, the availability of a large quantity of images to analyse, and data to confirm the respective identifications and diagnoses.

In the case of plant pest recognition, the equivalent of such “low-hanging fruit” is likely to include weed seed recognition and the use of AI to recognise such feature/states as wing venation of certain winged insect pests. Since the AI application currently being developed in New Zealand for the identification of the brown marmorated stink bug (BMSB), mentioned earlier in section 2.6, concerns a limited number of New Zealand-native species and established relatives, is also likely to be successful.

More ambitious applications of AI to the recognition or diagnosis of quarantine pests are not likely to be constrained by the AI technology itself but with accessing the data required for training the technology. Many projects that have embarked on an AI approach have found that acquiring enough images to give anything close to a reasonably high level of recognition or diagnostic success requires a much larger investment than initially envisaged.

Not only does imaging quality need to be improved, as well as the consistency, coverage, and availability of images, but currently, there is no efficient mechanism to authenticate and facilitate the sharing of the large number of images accumulating to train AI-assisted image recognition tools. Images must also include metadata reflecting validated identifications and other associated data to ensure AI training is based on the correct taxa and not on misidentified images. Once again, local expert taxonomic or diagnostic information associated with these images needs to be available during the AI training process.

Finally, as stated several times in this review, the future role of DITs is likely to involve a mix of various online and app keys, images, and other digital tools, together with complementary molecular and other lab-based techniques, as well as field identification and diagnostic procedures. The extent to which AI will play an important future role in this context is unclear, including the latest AI development - ChatGPT.

Judging by the experience gained in the use of AI for medical diagnostics, chess, and other AI applications, the most effective AI results are likely to occur when AI is used in combination with human expertise. This again raises the important issue regarding the future role of taxonomy. Many current practicing taxonomists, particularly those experienced in plant and animal species of biosecurity concern, are either close to or already in semi-retirement. We believe it is critical to arrest this taxonomic decline, train parataxonomists, or find other ways of maintaining the basic taxonomic skills necessary to authenticate future developments and applications of DITs for plant biosecurity.