Forensic Science International: Animals and Environments 1 (2021) 100007

Contents lists available at ScienceDirect

Forensic Science International: Animals and Environments

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

Original Research

Countering plant crime online: Cross-disciplinary collaboration in the FloraGuard study

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ARTICLE INFO

Keywords:
Artificial intelligence
CITES
Cross-disciplinary
Cybercrime
Natural language processing
Illegal wildlife trade

ABSTRACT

The illegal online trade in plants has potentially devastating impacts upon species poached for sale in digital markets, yet the scale of this threat to endangered species of flora remains relatively undetermined. Effectively monitoring and analysing the online trade in plants, requires an efficient means of searching the vastness of cyberspace, and the expertise to differentiate legal from potentially illegal wildlife trade (IWT). Artificial Intelligence (AI) offers a means of improving the efficiency of both search and analysis techniques, although the complexities of wildlife trade, and the need to monitor thousands of different species, makes the automation of this technology extremely challenging. In this contribution, we review a novel socio-technical approach to addressing this problem. Combining expertise in information and communications technology, criminology, law enforcement and conservation science, this cross-disciplinary technique combines AI algorithms with human judgement and expertise, to search for and iteratively analyse potentially relevant online content. We suggest that by coupling the scalability of search algorithms with a sufficient level of human input required to evaluate wildlife trade data, the proposed methodological approach offers significant advantages over manual search techniques. We conclude by examining the high level of cross-disciplinary collaboration required to develop this technique, which may provide a useful case study for conservation practitioners and law enforcement agencies, seeking to tackle this technology-driven threat to biodiversity.

1. Introduction

Research demonstrates that an illegal trade in plants is flourishing online [1,2]. Illegally harvested plants are traded online as live horticultural specimens, medicinal products and timber, helping to drive poaching activity that can devastate populations of targeted species, and place them at risk of extinction (see Appendix for examples). Most research into this understudied branch of the illegal wildlife trade focuses on species listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which aims to ensure that the international trade in species vulnerable to over-harvesting, is conducted sustainably. Enforce since 1975, CITES regulations evolved around a system of paperwork and physical border checks, and face new challenges in the regulation of Internet trade. For instance, the use of postal and courier services enables online traders to circumvent border checks, while a lack of standardised regulations relating to Internet trade, further complicates the task of prosecuting crimes spanning multiple legal jurisdictions [3]. More than 30,000 species of plants including orchids, cacti, cycads and many timber species are listed in the CITES Appendices, yet the threat of illegal online trade is not confined to these highly protected plant groups. Evidence increasingly shows that the Internet is also used to illegally exploit a wide range of other species, not listed by CITES, but that are under the protection of national and regional laws [4,5].

The Internet's role in facilitating the illegal wildlife trade (IWT) receives increasing attention from conservation researchers and global enforcement agencies [6–9]. Unlike other forms of cybercrime, which exist purely in the digital realm, "Internet-facilitated IWT" represents a hybrid of online and offline activities. This, combined with the specialist nature of wildlife products and the flexibility of cyberspace, makes detecting and deterring these crimes beset by technical and legislative challenges, in need of urgent, innovative solutions.

Fundamental to the challenge facing researchers and enforcement agencies, is the sheer volume of Internet traffic. With 4.5 billion global users, the Internet provides wildlife traffickers with a vast consumer base. Naïve or novice buyers may purchase wildlife products without knowledge of their conservation status or legislation intended to ensure their sustainable trade. Of greater conservation concern, are the connections easily made in cyberspace between vendors and specialist collectors of rare and threatened species [10–12]. A second challenge arises due to the ways in which illegal trade can mimic a frequently more

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http://doi.org/10.1016/j.fsiae.2021.100007
Received 30 December 2020; Received in revised form 9 April 2021; Accepted 25 April 2021
Available online xxx
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extensive trade in similar looking, legal wildlife products. This is particularly true of the trade in plants, where cultivated and wild sourced specimens can be hard to differentiate from online sources alone. This requires skills in species identification, and a detailed knowledge of the conservation policy legislation surrounding their trade. With thousands of plant species in trade, many of which bear close resemblance to one another, the interpretation of online content relating to their sale, requires considerable experience and expertise.

The existence of parallel legal and illegal trades creates a “needle-in-the-haystack” effect, with relatively low incidences of illegal trade obscured by large volumes of legitimate online content. This makes the detection of potentially illegal trade using conventional search engines inefficient, due to the time required to manually perform these searches [13]. Focusing on specialist websites as “cyber-hotspots” of activity does not alleviate the problem, with hundreds of specialist interest groups attracting thousands of international members, with trade possible across a significant proportion of these platforms [14].

In response, conservation and enforcement teams are increasingly exploring the use of Artificial Intelligence (AI) algorithms, to direct searches for relevant online “posts” (here, defined as any form of message published in an online setting) [15]. To preserve valuable resources, AI solutions for monitoring online wildlife trade would ideally operate with minimal human supervision. The inherent difficulty in assessing the online trade in plants, however, presents a significant challenge to development of software capable of working with a high degree of automation (see, for instance [16]). Ensuring that captured data of interest can be efficiently reviewed by human investigators, remains an important consideration.

In 2018, the FloraGuard team set out to incorporate these concepts into a methodological approach combining the efficiency of AI search tools, with a suitable level of human-led data analysis. A key objective was to create a workflow capable of generating intelligence to inform both conservation policy relating to the illegal online trade in plants, and, potentially, real world law enforcement operations. This required a highly cross-disciplinary approach, combining expertise in conservation science, criminology, law enforcement and information and communications technology (ICT), which we believe provides an instructive case study for future collaborative work in this field.

This paper reviews the creation and assessment of a novel, socio-technical approach to Internet-facilitated IWT investigations. For the purpose of this paper, we will focus on the role played by conservation science and its interactions with the other disciplines involved in the project. We will also explore some of the broader challenges surrounding the use of AI technology, to counter the illegal sale of endangered plants online. The paper concludes by considering the advantages and limitations of the proposed socio-technical approach, and its potential as an investigative tool for both research and law enforcement.

2. Our methodological approach

2.1. Development of a socio-technical workflow

The methodological approach developed combined a suite of AI tools with human expertise to create a novel socio-technical workflow for investigating Internet-facilitated IWT (Fig. 1). Here, we focus on its application in conservation science, with a focus on the illegal online trade in plants.

The step-by-step guide below highlights the disciplines involved in each stage:

Step 1. Identify species of interest

Species of interest were selected according to the following criteria:

i Species listed in the CITES appendices.
ii Species of high conservation concern, threats include illegal harvesting.
iii Species known to be traded in online settings.

Selection was informed by: 15 semi-structured interviews with conservation and enforcement practitioners (discussed further in [13]); preliminary research performed by conservation scientists at the Royal Botanic Gardens, Kew; and Internet searches indicating the likelihood of online trade.

Step 2. Develop search lexicon

To direct the search tools, lexicons containing key words and terms relating to online trade in the selected species were created (see supplementary materials). These comprised:

i Accepted Latin names, Latin synonyms, vernacular names, common misspellings (conservation scientists).
ii Trade names (law enforcement experts) and informed by preliminary online searches.
iii Predicate terms indicative of certain online behaviours (e.g. “buy” “sell” “swap”) (criminologist and ICT scientist).
iv Excluded terms (e.g. for one species group, the term “seeds” was excluded, to focus the search on the trade in live specimens) (conservation scientists).

Step 3. Preliminary website search and evaluation

To identify websites of potential relevance, manual searches using conventional search engines were conducted, directed by key words selected from the search lexicon. Search results were assessed by the criminologist and conservation scientists, to identify websites connected to trade in the selected species.

Step 4. AI enabled searching of selected websites

AI search tools were applied by the ICT scientist to the websites identified in Step 3. Directed by the entire search lexicon, these identified and extracted relevant content, in the following two-stage process:

I Web crawling[1] : Crawling software systematically downloads all pages in the target website, saving them as an HTML data set.
II Parsing: Parsing software identifies relevant text and metadata within HTML datasets. The Parsed data was stored as JSON files containing relevant sentences and metadata (such as author name and timestamp). The remaining website content was discarded.

Step 5. Criminology analysis

The parsed data was manually explored by the criminologist to identify content of relevance including:

i Evidence of potentially illegal trade.
ii Entities of interest (key actors, places, organisations, events, websites, additional species ofpotential relevance).
iii Associated conservation issues.
iv Relevant subcultural factors.

Relevant data was coded using coding software, according to a bespoke framework developed during the analysis. Further details can be found in [17].

Step 6. Conservation science and specialist botanical advice

Data identified in Step 5 requiring specialist knowledge was analysed by conservation scientists. This included an assessment of technical terms, alternative species names, and images of specimens in trade. Where necessary, advice from botanical specialists with deep knowledge of the species in question was sought. Conservation science advice was returned to the criminologist, to inform the qualitative analysis.

Step 7. AI enabled information extraction (IE) and visualisation of data

Relevant online posts identified in Steps 5 and 6, can now be returned to the ICT team, for information extraction (IE) and visualisation. An AI Natural Language Processing (NLP) algorithm examines the selected posts, extracting relevant information based on the search lexicon. To plot

[1] See [17] for a more detailed explanation of ICT terms.

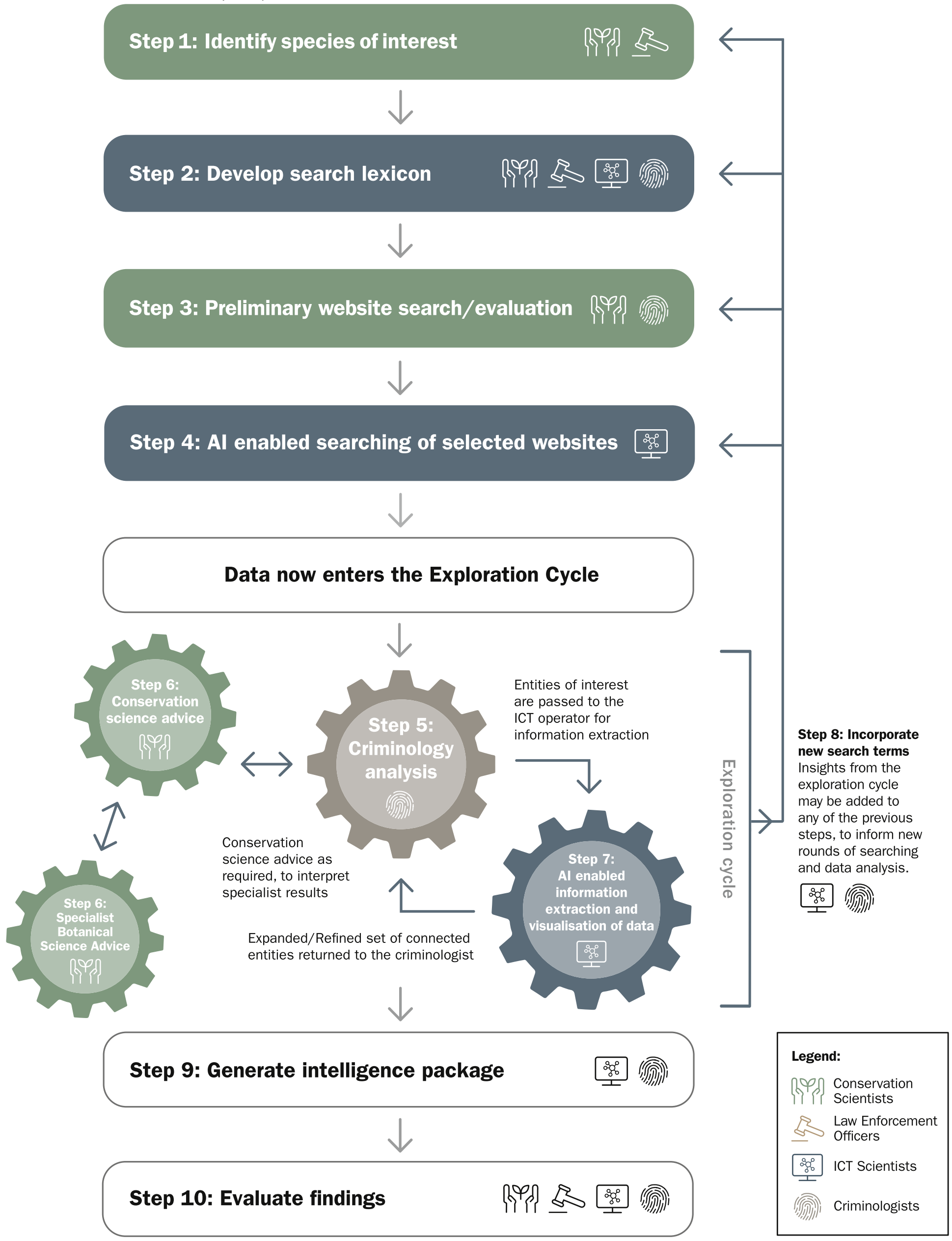

Fig. 1. Socio-technical workflow for the investigation of Internet-facilitated IWT, developed during the course of the FloraGuard study. Adapted from [17].

and visualise the extracted data, the mentioned entities, authors and post/thread connections are indexed and filtered. Specialised software[2] then presents the data as a Named Entity (NE) Directed graph, as an aid to further data analysis (Figs. 2, 3 & 4).

Step 8. Incorporate new search terms

To enable a comparison of the efficiency of AI tools with human performance, Step 7 was performed in parallel to the qualitative criminology analysis. In the full, proposed, version of the methodology (Fig. 1), the loop between Step 7 and the rest of the workflow would be closed, to create a highly iterative exploration of the data. To perform this “Exploration cycle”, data shuttles between the qualitative analysis (Step 5) and information extraction (Step 7) processes. This enables entities of interest discovered by the criminologist to be examined by the AI tools, and connections between these and other entities within the data set to be found and visualised by the software. In turn, these visualisation outputs may then highlight new connections for the criminologist to evaluate. At any stage of the exploration cycle, new entities or terms of interest emerging from the analysis may be added to (or removed from) the search lexicon, for inclusion in a new round of searching. The updated lexicon may be incorporated into any previous stage of the workflow, with any updated (expanded or refined) data sets then re-entering the exploration cycle for a new round of iterative analysis.

Step 9. Generate intelligence package

This is a human summary of intelligence, based on the conversion of AI results to lists of relevant entities based on the POLE classification system (People, Object, Location, Event). Includes: NE graphs to show community inter-connections; extracts from original posts as evidence and source provenance; criminology analysis; and criminology conclusions.

Step 10. Evaluate findings

We believe the intelligence package has potential use for i). conservation scientists to inform conservation policy decision making, and ii). law enforcement agencies to inform intelligence led investigations, or as corroborating evidence to support prosecutions.

[2] Matplotlib and networkx packages which work with Python data to create interactive visualisations.

Evaluating use of the intelligence package would provide valuable feedback to aid the design of future investigations.

2.2. Ethical considerations

The methodological approach was conducted in line with existing standards for online research, [18–20], and in accordance with the University of Southampton ethical approvals ERGO/FPSE/41,260 and ERGO/FPSE/46,393[3] .

Searching was restricted to open-source websites with web pages discoverable by search engines without the need to use website login details. This ensured that any posts contained within the data set were those that had been made manifestly public by the data subjects. Additional data protection considerations were also made regarding the suitability of any content for crawling and inclusion within an aggregated data set, to ensure that any potential risks to data subjects were minimised. For instance, to protect the identities of named entities, all published data was programmatically pseudonymised, regardless of context[4] . Searches were limited to the surface web, with no searches conducted on the deep or dark web[5] . This was for pragmatic reasons (most IWT is known to occur on the surface web), and also involved fewer risks to the researchers that might arise from dark web investigations.

2.3. Evaluation of the methodology

The performance of the methodology was evaluated in terms of:

a Search efficiency:

(i) Number of relevant online posts identified, measured against the time and resources required. This includes an evaluation of the information extraction tool, by measuring the number of entities connected to a target suspect detected by the algorithm, as a fraction of those identified through manual criminology analysis (the “AI recall score”).
(ii) Performance of the AI tools, as an aid to data analysis.

b Search effectiveness:

(i) Potential use of the intelligence, in law enforcement operations.
(ii) Potential use of the intelligence, in conservation science.

3. Results

We identified a range of plant groups meeting the criteria set out in Step 1 of the methodological approach, three of which were selected for use within the study (Table 1).

Following Step 3 of the methodological approach, nine websites of interest relating to the selected species were identified (Table 2).

3.1. Search efficiency

Plant groups were separated into case studies, examined over 10 working days. The first five days examined trade in *Ariocarpus* species, and the second, trade in *Euphorbia* species and *Saussurea costus*. Automated web crawls were conducted overnight, approximately five rounds of searching performed per case study. Around 25 h of the criminologist’s time was required to qualitatively analyse the search results returned by the AI search tools (50 h total for all case studies). This measurement enabled the relative efficiency of the methodological approach to be assessed (Table 3). Each case study also required the active involvement of ICT and conservation scientists, although their overall input was harder to measure. See supplementary materials for an overview of the entire resources required to perform the methodological approach in full.

To enable the performance of the AI information extraction (IE) algorithm to be evaluated, information extraction was conducted in parallel to the qualitative data analysis (rather than as part of a completed “exploration cycle” – see Step 8, Section 2.1). The performance of the algorithm was then compared to that of the criminologist, whose own analysis formed a “ground truth” baseline. We used the standard information retrieval recall metric, which measures the number of ground truth entities successfully identified, as a fraction of the total number of ground truth entities available, to provide a “recall score” (Table 4).

3.2. Search effectiveness

Once target suspects were identified, Named Entity (NE) Directed graphs allowed their connections with other entities to be visualised. These visual outputs enable the relationships between entities to be rapidly interpreted for potential use as intelligence (Figs. 2, 3 and 4). NE directed graphs have various parameters to control their inputs and “depth” (layers of connections between entities). To aid analysis, the graphs contain the following information:

- Node colour = Named entity type.
- Node size = number of connections (globally).
- Line width = number of connections between entities (conversations).
- Line numbers indicate line width. These are not involved in the analysis of the graph.

The visualization is interactive and can be zoomed in to allow dense data to be explored. As entities retain their post identifier, their “conversational context” can be traced and followed, enabling the original data to be returned to and examined as a chronological online conversation. The IE algorithm developed during the FloraGuard study is open-source[6] .

NE directed graphs can be analysed or “read” using a “graph walk”. This involves following the connections between target suspects and other nodes on the graph (which may be posts, authors or forum threads), in both forward and backward directions. For instance, a graph walk may reveal that an author who made post (a) is contained in a specific forum thread (b) which also contains post (c) which mentions named entity (d). We could also imagine this in a more shorthand form (with “Joe” and “Bill” our imaginary suspects in this case):

Joe -> Post(Joe) -> Thread(X) -> Post(Bill) -> Mentions (e.g. species/location/organisation).

This enables posts to be examined not only in isolation, but in connection to other posts which may also be of relevance to the trade in a particular species. In this way, the NLP tool’s extraction of “mentioned entities” creates a “conversational graph” around how they are connected. Human analysis of the context of these mentions is then required to make an evaluation and judgement of the online behaviour observed.

To illustrate, Figs. 2, 3 and 4 show the same target suspect as the central root node, surrounded by different depths of connected entity nodes from the data set. Fig. 2 shows that other entities are directly connected with the target suspect (depth 1) via four posts and four threads. In Figs. 3 and 4, each thread is then linked to posted information relating to trade activity, countries, locations, individuals and businesses (depth 2). Looking towards the right-hand side of Fig. 3, mentions of *Ariocarpus* (green) are connected to two of the forum threads. Using these identified threads as a focus, manual browsing of individual posts reveals

[3] For practitioners seeking to emulate this study, prior legal and ethical approval for research involving the processing of online data is essential, as is ensuring compliance with the relevant data processing laws of the country in which the research is being conducted.

[4] For a more detailed overview of the project’s ethical considerations, see [40]

[5] The term ‘surface web’ refers to static web pages, whose URI (uniform resource identifier) provides the same page every time, making them relatively searchable. ‘Deep web’ refers to areas of the internet less accessible to search engines, due to logins, paywalls or dynamic computing, which cannot be readily indexed as they are either inaccessible to crawlers or provide different content each time. The ‘dark web’ is accessible through the Tor network which uses certain protocols to provide users with anonymity.

[6] See https://github.com/stuartmiddleton/intel_viz_entity_graph.

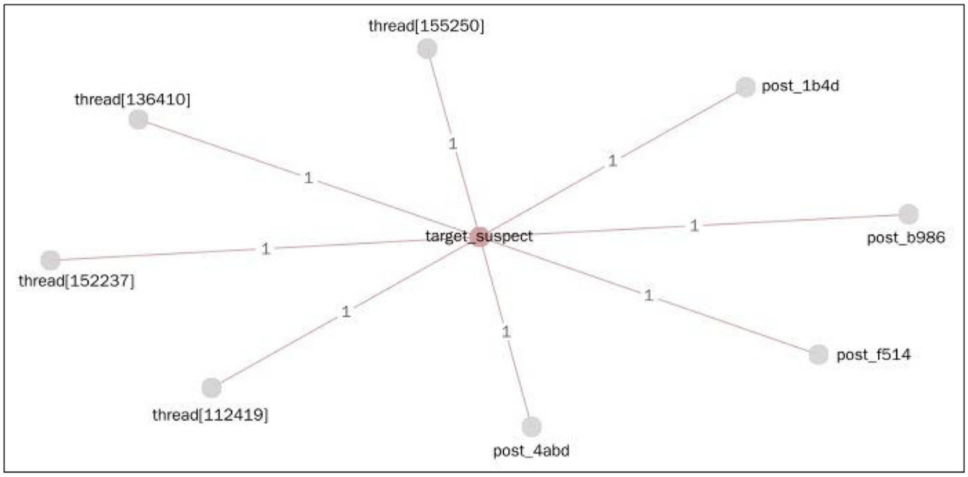

Fig. 2. Named Entity Directed Graph for a target suspect involved in *Ariocarpus* trade, with one deep connection. Real names and organisations have been pseudonymised.

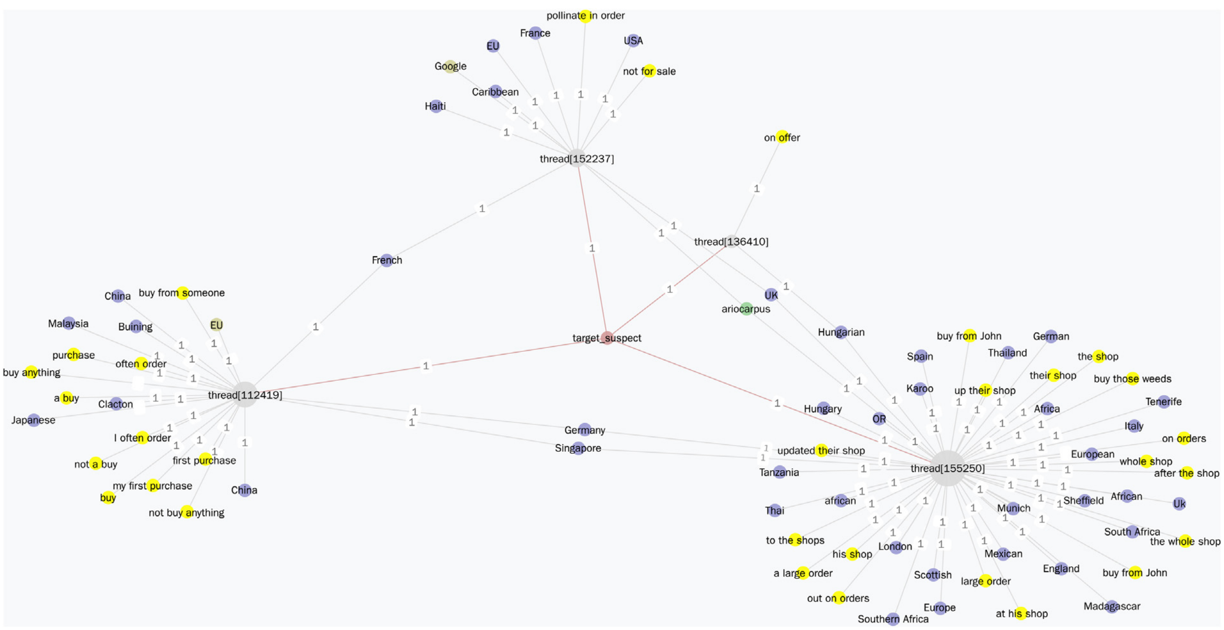

Fig. 3. Named Entity Directed Graph for a target suspect involved in *Ariocarpus* trade, with two deep connections. Target suspects are coloured red, plant references green, forum threads grey, behavioural predicates yellow, and locations purple. This graph hides posts and people to focus on behaviour and location. The real names and organisations have been pseudonymised.

that Hungary is a potential country of interest. This manual analysis might then identify further entities of interest, which can be added to the search criteria for the next cycle of analysis. Cyclic examination of threads, posts, authors and organisations may then incrementally build up a network of actors [21] and narrative around the circumstances of trade activity for *Ariocarpus* in this online community, which helps to reveal the likely origin, movement and sales activity surrounding these plants.

The graphs were found to have an upper limit of around 400 connected entities, beyond which they become too dense to read. For further details regarding the production of NE Directed graphs, see [22].

4. Discussion

4.1. Search efficiency

4.1.1. Number of relevant online posts identified, measured against the time and resources required

The use of a web crawler to search and download >68,000 online posts, represents a considerable efficiency in searching compared to the amount of time it would take to search for these posts using standard search engines. The AI led filtering of this data to create a subset of around 13,600 potentially relevant posts, made the creation of a large yet manageable data set possible, with minimal human processing of the data required to reach this point.

A difference between the ability of the AI tools to more accurately confirm the relevance of posts, compared to the number verified as relevant by the criminologist, was then seen (Table 3). From the subset of posts identified as potentially relevant by the AI tools, the criminologist found 5.6 % of posts relating to *Ariocarpus*, and 20.6 % relating to *Euphorbia* to be of further interest. As the criminologist also noted posts of broader relevance to species conservation, the number of posts relating to potentially *illegal* trade, comprised an even smaller volume.

The discarding by the criminologist of 80–95 % of posts initially selected by the AI tools, should not be regarded as a “failure” of the technology. The complexities of the online trade in plants include: the need to identify a wide range of species often similar in appearance and occurring online under a range of scientific, common and trade names; the need to differentiate between cultivated and wild sourced specimens

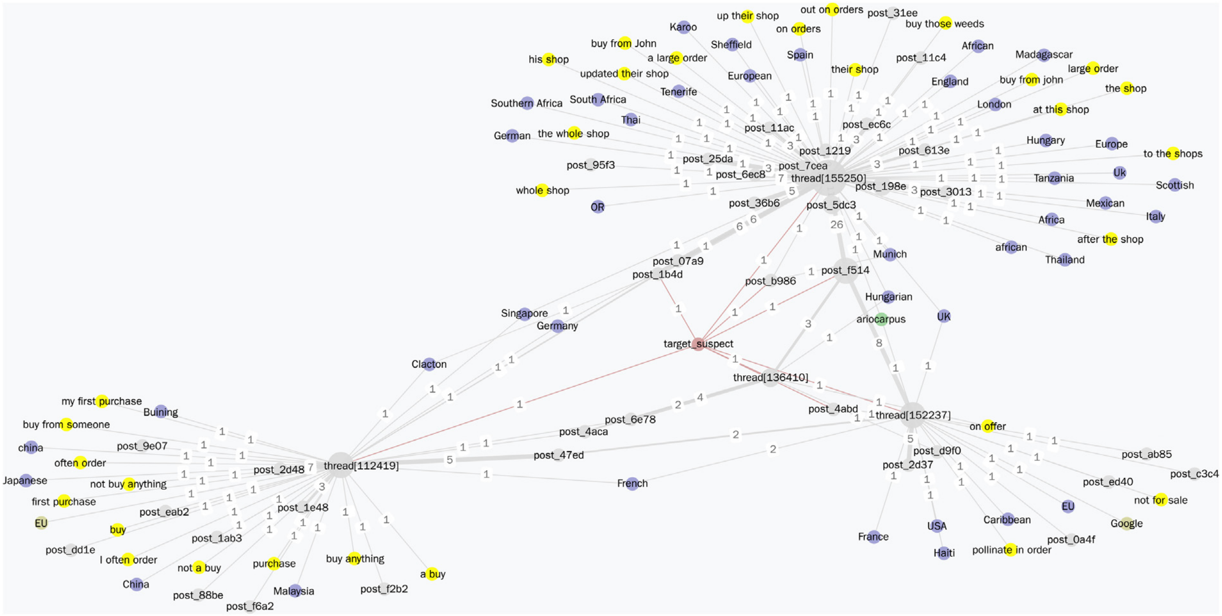

Fig. 4. Named Entity Directed Graph for a target suspect involved in *Ariocarpus* trade, with two deep connections. Target suspects are coloured red, plant references green, forum threads and posts grey, behavioural predicates yellow, and locations purple. This graph hides people to focus on behaviour, location and posts. The real names and organisations have been pseudonymised.

Table 1
The three plant groups of conservation concern selected for use in the study.

Plant Group	Selected Species	Country of Occurrence	IUCN Red List	CITES Appendix	Online Trade
Ariocarpus species	Entire genera (seven species and associated subspecies).	Mexico/Southern USA	NT - EN	I	Live specimens and seeds for horticulture.
Euphorbia species	13 species of succulent *Euphorbia* with restricted ranges (island endemics).	Madagascar/Canary Islands/Azores	VU – CR One species not assessed.	I / II	Live specimens and seeds for horticulture.
Saussurea costus	This is a single species.	India/Pakistan	CR	I	Roots and derivatives for medicinal use.

Table 2
Websites of relevance to trade in the selected species, identified by preliminary website search and evaluation, based on the search lexicon key words list (Step 3).

Website Shortlist	Nine Websites Selected							
Species of Interest	*Ariocarpus* spp.				*Euphorbia* spp.	*Saussurea costus*		
Website ID	Forum I	Forum II	Forum III	Forum IV	Forum V	Forum VI	Etsy	Ebay	Alibaba
Trade Purpose	Horticulture			Entheogens	Horticulture		Medicinal Products		
Website Type	Specialist interest public forums						E -commerce websites		
Website Layout	Topic themed threads						Product themed advertisements		
Content Type	Written posts between forum members, images						Product descriptions, images, shipping information, customer feedback, hyperlinks,		
Expected Products	Whole live specimens, grafted specimens, leaves, roots, cuttings						Whole roots, sliced roots, powders		
Language	English								
User Base	International								

which may closely resemble one another; and the fact that illegality is rarely clearly signposted by wildlife traffickers, making the use of proxy indicators of illegality essential. The difficulty that AI faces in interpreting these subtleties is to be expected. At present, the creation of "black box" fully automated AI models usually requires (a) training AI tools for a very specific purpose, requiring a lot of computer science effort to achieve an excellent accuracy and (b) restricting the use of the tools to specific problems, with significant effort required to re-train for new settings. The "broad spectrum" tool developed in this study necessitates less accuracy than more tailored AI approaches, but with a "human in the loop", has the ability to adapt to changing problems, and to be quickly deployed in new settings as required. This is particularly useful for investigating the illegal trade in plants, with potentially thousands of species in trade, across a wide range of online platform types.

Image recognition software was not included within the suite of AI tools developed in the FloraGuard study, but its potential to investigate Internet-facilitated IWT in flora, would face similar challenges and limitations. The narrow specificity of image recognition software and

Table 3
Overview of search data generated by a combination of AI search tools and manual criminology analysis. From left to right, the data set was gradually refined, moving from data capture and a broad analysis performed by algorithms, to fine-grained qualitative analyses requiring human expertise. *For this forum, the number of authors equalled the number of threads, as relevant posts each occurred in their own individual thread, giving each post both a unique author and unique thread. **The reason relevant posts confirmed for *S. costus* increased following criminology analysis, is discussed in section 4.1.1.

Selected Species	Websites	A Total posts crawled	Threads	Authors	B Potentially relevant posts identified by AI tools	C Relevant posts confirmed by criminologist	C as % of A	C as % of B	Hours criminology analysis	Relevant posts (C) identified/hr criminology analysis
Ariocarpus spp.	5	52,217	1218	3308	9676	543	1.0%	5.6 %	25	21.7
Euphorbia spp.	1	15,518	545*	545*	3733	768	4.9%	20.6 %	12.5	61.4
S. costus	3	1263	N/A	156	288	947	74.9%	328.8 %**	12.5	75.8
Total	9	68,998	1826	4009	13,697	2258				

Table 4
Recall scores for the Information Extraction (IE) algorithm, as a proportion ground truth entities successfully identified by the software. A mean recall of 1.00 would indicate that IE had discovered every ground truth entity identified by the human expert, in the criminology analysis.

Connection Type	Mean Recall			
	Ariocarpus spp.	*Euphorbia* spp.	*Saussurea costus*	All
People	0.34	0.78	N/A	0.56
Location	0.56	1.00	1.00	0.85
Plant Species	0.2	0.4	0.14	0.25
Organisation	0.33	0.14	N/A	0.24

large amount of prior training required to deploy it, means this technology is not yet suitable for detecting the subtle visual clues contained within plant images, that may indicate wild or illegal sourcing (see [17] pages 54–55). In the present study, the analysis of online images was therefore conducted manually, by conservation science and botanical experts. As the crawled data did not include downloads of images, a manual check of posts of interest was first required, to see if they contained images of relevance, although as HTML data sometimes provides an indication of a post's visual content, this process can be shortcut to some extent.

The benefits of human-led data analysis were most apparent when applied to the qualitative data contained within online forum posts. By comparison, e-commerce posts contained far less contextual factors to act as proxy indicators of illegality, making NLP analysis of these posts more difficult, and false positives/negatives more likely. In exploring online advertisements of *S. costus* products, the criminologist also manually opened website links contained within them, which provided access to information outside the original target domain. As this information was not accessible to the AI tools, this resulted in the number of relevant posts involved in the *S. costus* investigation *increasing* (+328 %) following criminology analysis, compared with the sub-set of posts originally identified by the crawling software. The training of AI tools to identify adverts or spam to enable the automatic crawling of webpages outside the target domain, requires further research work. In the current methodology, the scope of the tools is limited to specific domains (Table 2), with reliance on the criminologist to spot opportunities to search beyond this. While this adds to the amount of human input required, this ensures that investigations remain highly targeted, with new domains of interest then included within the next round of AI led searches.

When applied to the methodology in its entirety, "data-per-unit-effort" is hard to quantify. In terms of criminology analysis, some measure of "per-unit-effort" is represented by the number of relevant posts that were discovered per hour by the criminologist (Table 3). While investigations are always context specific, returns of between 21.7 relevant posts/hr (*Ariocarpus*) and 75.8 relevant posts/hr (*Saussurea costus*) represent a considerable enhancement to the number of posts that are likely to have been discovered using a manual, standard search engine approach. These figures should not be viewed as an absolute measure of search efficiency and have important caveats. Firstly, the criminology analysis was performed by a criminologist highly skilled in searching for online data, with slower rates of searching expected for less experienced data analysts. Secondly, the data did not appear in regular patterns or always in the same complexity, making it impossible to predict the volume of useful data that may be captured within a specific timeframe. Thirdly, performance from three case studies cannot be considered a representative sample.

To improve the efficiency of web crawls, the inclusion of multiple species within the same search lexicon proved effective. In the present study, we explored this approach through searches for plant groups comprising one, seven and 13 species. Combining taxa in this way also enables links between the trade in different species to be discovered more readily. The optimum number of species to combine, ultimately depends on the amount of data generated by each, and the amount of time available to analyse the potentially large data sets returned. Due to the small dimension of the research team, the study of trade in these species was limited to a total of nine website domains, to make manual analyses possible in our given time frame. The number of websites simultaneously crawled could, however, also be expanded, to create data sets of an appropriate size for the time and resources available to a research team. Indeed, as the criminology analysis was the most time-consuming stage of the workflow, this layer perhaps represents the greatest "limiting factor" to the scale and speed of an investigation. Increasing capacity for criminology analysis could quickly expand the scale and scope of an investigation, although beyond a certain point, this would need to be balanced by additional scaling up of the other core disciplines.

4.1.2. Performance of the AI tools as an aid to data analysis

As an aid to data analysis, our methodological approach offers a number of advantages compared to manual techniques utilising conventional search engines. Firstly, the initial filtering of data provided by the AI tools reduces the need for a lengthy "data cleaning" step. Secondly, the export of HTML data in database format enables large, qualitative data sets, to be more easily navigated. Thirdly, the use of information extraction tools to identify and visualise connected entities, enhances the human led analysis of the data, enabling new insights to be discovered more quickly.

Difficulties in interpreting the language used in association with illegal trade may account for the AI tool's less than perfect recall scores (Table 4). While the extent of any limitations to AI in this regard cannot be determined from this limited range of case studies, the identification by AI of fewer named entities compared to the criminologist, suggests the algorithm faced some difficulties in interpreting more subtle, contextual information relating to intentions or sentiments towards IWT. Additionally, the AI lacked access to additional contextual information outside the target web domain (e.g. a suspect vendor's home page), which may have been available for human analysis. An important compensating factor in this regard, is that when extracting and visualising connected entities, the AI tools work in partnership with the criminologist, rather than in isolation. This means that if the AI misses a connection, the human may compensate and vice versa, making the methodology more powerful than the sum of its parts. Examining ways to improve the recall score of the AI tools compared with human analysis, for instance through use of new NLP techniques, is a focus for future work.

4.2. Search effectiveness

4.2.1. Potential use of intelligence in law enforcement operations

As AI generated evidence is usually not 100 % interpretable and repeatable, its use as admissible evidence in a court-of-law remains extremely challenging. While producing such evidence was not among the study's objectives, we believe that by increasing the scale of web page analysis, and better focusing human investigative effort, our methodology has potential to generate open-source intelligence to inform law enforcement operations. Indeed, this type of intelligence is already utilised in many IWT investigations [23].

In the proposed approach, an intelligence package based on NE directed graphs could be categorised in a similar way to the existing UK law enforcement standard POLE (People, Object, Location and Events). Its assessment would be based on the "balance of probability" that a suspect may be engaged in illegal activities. For instance, entities connected to a target suspect may include plant nurseries, plant shows or certain countries, suggesting their potential role within plant smuggling networks. While not offering proof, this may lead investigators towards other sources of admissible corroborating evidence, or support evidence already found in other settings to help determine that a wildlife crime has taken place.

A socio-technical approach to data gathering has the added advantage of making the AI search results increasingly verifiable and explainable. This increases trust in AI tools, avoiding concerns surrounding "black box" AI techniques, where the accuracy and potential bias of AI tools may be called into question [24]. In addressing these concerns, ensuring the correct online investigatory and data handling procedures are followed is also of crucial importance, which must be factored into both data gathering and safe storage techniques.

4.2.2. Potential use of intelligence in conservation science

Examining online trade in rare and endangered species, enables the risk of overharvesting to meet market demand to be more accurately assessed. Evidence that illegally sourced specimens are entering international trade, may support proposals for protective CITES listings to be strengthened or applied to currently unlisted species. Regular searches to monitor trade in high risk species, or horizon scanning for new trends in trade, could inform a wide range of conservation measures, such as alerting management authorities to new species-specific developments, or the deployment of rangers to areas of concern.

A detailed analysis of online markets can also generate valuable insights into the drivers of illegal wildlife trade. For instance, the FloraGuard case studies revealed that some online users exhibiting suspicious behaviour, held an interest in a number of plant groups, with one suspect linked to both *Ariocarpus* and *Euphorbia* species. Establishing links between the trade in different species builds a more comprehensive picture of plant trade than considering individual species in isolation, and could reveal valuable insights into the scale and organisation of illegal plant trading networks. Trade in endangered species was also found in unexpected online settings. Of the six forums searched, two were of relevance to *Ariocarpus* due to the use of these plants for their supposed entheogenic properties (Table 2). Posts suggesting wild sourced plants were changing hands were detected (see [25] for a detailed analysis of these entheogenic forums) illustrating the value of keeping an open mind when conducting searches, and conducting detailed research into species of interest to establish the variety of ways in which they may be utilised.

Valuable insights into the behaviours and attitudes of online users were also revealed. Negative attitudes towards plant conservation were justified by so-called neutralisation techniques, a term describing the categories of excuses that perpetrators use to justify actions that contravene laws or social norms [26]. Pro-conservation attitudes were also in evidence. These attitudinal insights provide a deeper understanding of the online horticultural trade in endangered species, suggesting areas where softer interventions, such as awareness raising or behaviour change initiatives, could be made.

4.3. Reflecting on our cross-disciplinary approach

Our methodological approach required a diverse combination of specialised expertise. While each discipline performed specialist tasks, a cross-disciplinary exchange of information was often essential for their successful execution. Knowledge transfer occurred between disciplines at both designated stages of the workflow and more organically, as key inputs and outputs were produced (Fig. 5). Bringing together diverse disciplines in this way, enabled all of the socio-technological aspects of Internet-facilitated IWT to be addressed, and may provide a useful case study for conservation practitioners and law enforcement agencies, seeking collaborative solutions for tackling this technology driven threat to biodiversity.

As certain key tasks require specialised skills, the potential scaling or wider use of this approach may hinge on the extent to which non-ICT specialists can be trained to perform the methodology with proficiency. For example, before being deployed, the web crawler must first be configured to each target website domain, making the methodology a dynamic tool kit requiring ICT expertise to operate, rather than a static plug-and-go product.

5. Conclusion and recommendations

The Internet's scale, global connectivity, anonymity, and lack of regulation provide perfect conditions in which conservation is threatened. In tackling these crimes, AI offers conservation science potentially game-changing solutions, although our findings underscore that in many wildlife trade scenarios, the complexities of online trade remain too subtle for AI tools to execute in isolation. The trade in plants provides a good example of the very specific challenges involved, with human expertise ultimately required to verify species identify, plant provenance, and the likelihood of illegal trade.

Increased automation of AI systems capable of detecting IWT remains an important objective to strive for, to minimise the human input required for investigations, and to enable a more systematic monitoring of cyberspace to be performed. The socio-technical approach reviewed here, couples the scalability of AI with the subtlety of human expertise, to interpret and verify the algorithms' findings. While not suitable for big-data style monitoring of cyber-space, this hybrid AI-human approach offers considerable efficiencies compared with manual investigation techniques utilising conventional search engines.

While the reliability of AI in detecting Internet-facilitated IWT will only improve, translating AI findings into real world action, requires results to meet a widely accepted threshold of confidence. Embedding a layer of human analysis within the data gathering stage is likely to be beneficial, even vital, in addressing this challenge. The traceability of posts back to their online source is also an important function of our approach, that enables data to be independently reviewed, as would be required in a court of law.

To keep pace with the online trafficking of wildlife, the use of AI technology must be regarded as a means of both catching criminals in the act, and informing conservation policies that deter potential poachers before they strike. For instance, regular assessments of the threat to

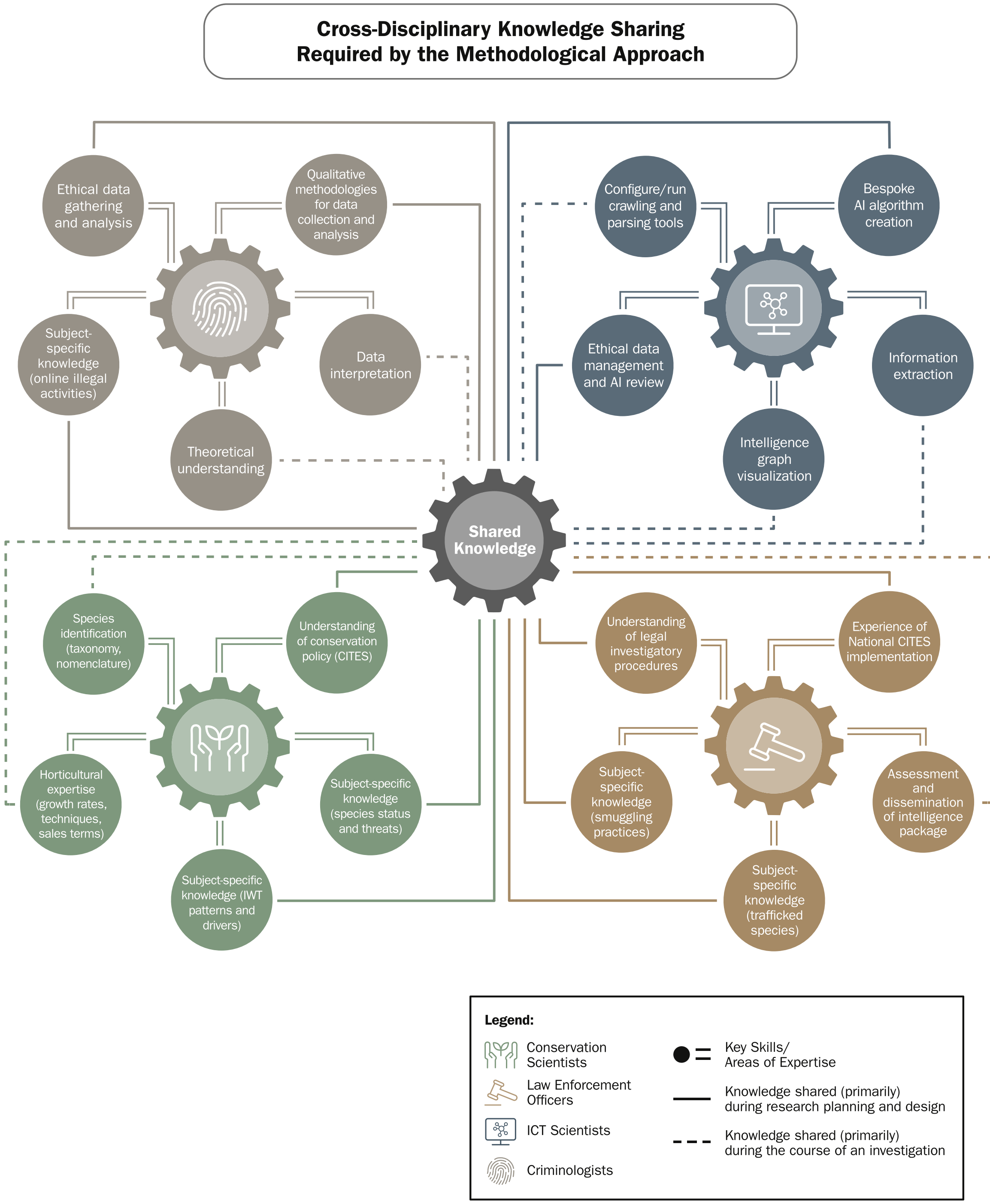

Fig. 5. Cross-disciplinary knowledge sharing required by the methodological approach, illustrating the "top five" areas of skills and experience that were required from each of the four disciplines involved.

species posed by online trade, could be used to inform on the ground protection for specific plant populations, while qualitative insights from data analysis could inform targeted information campaigns, raising awareness among consumer groups.

Where poaching cannot be averted and illegally sourced plants appear online, law enforcement, informed by the digital clues this generates, must be provided with adequate resources and powers, to act as an effective last resort.

As demonstrated by the present study, the use of AI techniques to generate high quality data still requires considerable cross-disciplinary collaboration. To capitalise on the rapid development of AI, establishing and maintaining working relationships between conservation science and the AI technology sector, can only help to accelerate its application within conservation initiatives. This could be achieved through collaborative project work such as this, and via workshops and seminars that provide opportunities for regular cross-disciplinary conversations. An improved understanding of AI's capabilities may enable conservation to take advantage of developments emerging in other application domains and identify conservation projects where new technologies might be tested.

In meeting future biodiversity targets, the potential for Internet-facilitated IWT to evade regulation and undermine ambitious conservation goals, must be recognised. This requires keeping pace not only with advances in technology, but also with developments in the management of the Internet and the perceptions of its use within society. The socio-technical approach reviewed here, offers a means of overcoming some of the current technical challenges posed by Internet-facilitated IWT, while deepening our understanding of the human dimensions behind it. We hope these insights provide a useful example of how cutting-edge AI technology can be embraced, to make the Internet a safer place for rare and endangered plants, rather than remaining an easy means of their exploitation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

D. Whitehead: Writing - original draft, Visualization. **C.R. Cowell:** Data curation, Supervision, Visualization, Writing - review & editing. **A. Lavorgna:** Conceptualization, Data curation, Funding acquisition, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing - review & editing. **S.E. Middleton:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing - review & editing.

Acknowledgements

This work was supported by the Economic and Social Research Council, ES/R003254/1. We thank Leigh-Anne Bullough (Royal Botanic Gardens, Kew), for her constructive comments on an earlier version of this manuscript, Guy Clarke MBE (UK Border Force), for his helpful feedback on the cross-disciplinary approach outlined in Fig. 5, and Ines Stuart-Davidson (Royal Botanic Gardens, Kew), for her creative input into the design and layout of Figs. 1 and 5.

Appendix A

Table A1

Table A1
Overview of the Internet's role in facilitating illegal trade in a range of plant groups. These examples illustrate how a small number of illicit traders can take as significant toll upon wild plant populations, placing species at risk, depleting ecosystems, and depriving local communities of important natural resources.

Plant Group	Overview of Internet Trade	Illustrative Case Studies	Conservation Implications
Orchids	A wide range of orchid species are traded for horticulture, food, medicinal and cosmetic purposes, with some online platforms thought to facilitate the sale of wild collected plants [14,27]. Orchid markets are divided between a majority of consumers who typically buy mass-produced plants, and a smaller group of specialist collectors, to whom rare orchids hold particular appeal, with trade in these settings of much greater conservation concern [28].	In 2009, the Vietnamese orchid *Paphiopedilum canhii* was first described to science. During 6 months of exploitation, 99.5% of wild specimens are thought to have been collected for the horticultural trade (an estimated 10,000–15,000 specimens). Details and images of the plant posted online stimulated demand and raised prices, with sales to overseas territories conducted in breach of CITES regulations [29].	Due to their widespread demand, and the fact that many species appear similar when not in flower, all approximately 28,000 species of orchids are listed in the CITES appendices. While in many cases, large scale artificial propagation is possible, the effective regulation of their production is important, in order to place controls on wild harvesting and avoid potential species extinctions in the wild.
Cacti	Cacti are extensively traded online for horticulture, and as extracts in food supplements and cosmetic products. A study of online trade conducted in 2010, found that in sales of 1000 live specimens (all CITES Appendix I species), almost 90 % of transactions appeared absent of CITES controls [12]. A 2016 assessment of the online availability of the genus *Strombocactus*, drew similar conclusions regarding a frequent lack of CITES documentation surrounding online sales, citing the Internet as an "open-door" for illegal trade [2].	In 2019, specimens of *Sclerocactus parviflorus subsp. havasupaiensis.* were found to be auctioned on ebay, raising suspicions that these had not been artificially propagated. This CITES Appendix II cacti is endemic to Havasupai Canyon (inside the Grand Canyon), where poaching is suspected to have occurred [30].	Based on IUCN Red List assessments, Cactaceae is among the World's most threatened taxonomic groups, with unscrupulous collection from the wild recognised as a significant driver of extinction risk for a wide number of species [31]. Cactus poaching in Mexico and the Southern United States is well documented, placing species at risk and disrupting efforts to map and conserve them [32]. Protecting cacti in range States consumes valuable conservation and enforcement resources – for instance Saguaro cactuses are now microchipped, to track their "movements" [30].
Medicinal Plants	Globally, around 26,000 plant species are documented to be of medicinal use [33]. A considerable number of these are in international trade. A 2017 e-commerce survey examining online trade in 365 CITES-listed medicinal plant species found that only 52 of >360,000 e-bay items, and 6 of >300,000 Amazon items, mentioned CITES in their descriptions. The trade observed was difficult to interpret due to limited use of common names within searches, and difficulty in assessing trade volumes and the proportion of international sales. The researchers recommended further study of 26 species and genera, due to particularly high online demand [34].	In 2007, 2500 mail packages of weight loss products containing *Hoodia gordonii* were seized by Sydney Post services in Australia. This species is listed in CITES Appendix. II and requires permits for international trade. Orders for the packages were placed online [35].	An estimated 60−90% of medicinal and aromatic plants are collected from the wild. Worth a reported US$ 3 billion globally, the economic value of this trade increased three-fold between 1999 and 2015 [36]. There are concerns that the Covid-19 pandemic may add to the pressures on some species, by both increasing demand for medicinal products, and as a source of alternative income during a period of economic turmoil [37]. Regulating the online trade in medicinal and aromatic plants is complicated by their use in a range of products and forms, and the use of opaque trade names and ingredients lists. The FloraGuard study found that e-commerce in *Saussurea costus* products observed in the study, appeared to be conducted largely absent of CITES controls [17].

Table A1 ***(continued)***

Plant Group	Overview of Internet Trade	Illustrative Case Studies	Conservation Implications
Timber	Timber is traded online in huge variety of forms, from logs and sawn wood, to furniture, flooring, and tools. Despite widespread illegal logging, few studies have focused on the Internet's role in facilitating the trade in raw timber and finished products.	In 2004, EIA/Telpak research into trade in merbau logs (*Intsia* spp.), found evidence of illegal trade originating from Papua Province, by monitoring online timber trade bulletin boards. Postings suggested monthly offers to sell timber of 118,000m^3, matched by monthly demand from prospective buyers (companies based in China or India) of 115,000m^3. Annually, this trade would total 1.5 million m^3 of merbau logs, all of which would have been illegal under Indonesia's log export ban [38].	A variety of verification schemes exist to help vendors and consumers identify sustainably sourced timber. Nevertheless, the role of the Internet in enabling the sale of illegally sourced products, or helping to coordinate illegal logging activities, is worthy of closer examination. See [39] for a discussion of the use of online data, in timber trade investigations.

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fsiae.2021.100007.

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