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REVIEW

An evidence map and guide for using community science, remote sensing, and environmental DNA for rare plant detection

Ana Hernández Martínez de la Riva[1] | **Trina Rytwinski**[1,2] | **Matthew Spetka**[1] | **Joseph R. Bennett**[1,2]

[1]Department of Biology, Carleton University, Ottawa, Ontario, Canada

[2]Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, Ontario, Canada

Correspondence
Ana Hernandez Martinez de la Riva, Department of Biology, Carleton University, Ottawa, ON, Canada.
Email: anahernandezmartine@cmail.carleton.ca

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Abstract

Field surveys have been the standard method for conducting species monitoring. However, other methods involving data from community science, remote sensing, and environmental DNA (eDNA) are increasingly being recognized for their potential as complements to traditional surveys. This evidence map examines studies that use these techniques for detecting rare terrestrial vascular plants. We explore plant types detected, study habitats, and recommendations for future research. We also use a case study of Canadian plant species at risk to suggest species that might potentially benefit from being detected via these techniques. We find that herbaceous species are the most common vascular plant type detected in community science and eDNA studies, while trees dominate remote sensing studies. Most community science studies occurred in urban areas, while most remote sensing studies occurred in areas that comprised multiple habitats, and most eDNA studies occurred in semi-open habitats such as shrublands and wetlands. Few studies discussed the efficacy of these techniques in terms of detection success and resources used. To better situate these new techniques among monitoring options, we discuss common problems, potential solutions, sources of false negative and false positive errors, and financial cost considerations for each technique.

KEYWORDS

citizen science, detectability, drones, eDNA, endangered species, monitoring, satellite imagery

1 | INTRODUCTION

Rare plant species are those that occur in small geographic ranges, require specific habitat conditions for their survival, and/or occur in small population sizes (Rabinowitz, 1981). As such, these species are particularly vulnerable to threats (Hernández-Yáñez et al., 2016), and understanding their population dynamics is crucial if we want to implement measures to protect them. However, determining if a species population is increasing, stable, or decreasing can be challenging since there are numerous factors that may affect the

detectability of an organism, such as species characteristics (e.g., abundance, occurrence patterns, morphology, phenology; Chen et al., 2013; Kéry et al., 2006) and survey characteristics (e.g., survey site complexity, survey area, surveyor experience, survey effort; Dennett et al., 2018; Hauser et al., 2022). In addition, many areas remain under-surveyed for rare plants (Rosner-Katz et al., 2020), and the threat status of many rare plants remains poorly understood due to lack of data (Antonelli et al., 2023).

Field surveys have been the standard method for conducting species monitoring. However, other methods involving data from community science, remote sensing, and environmental DNA (eDNA) are increasingly being recognized for their potential as complements to traditional surveys to increase the number of overall detections for rare plants.

Community science (aka "citizen science"), as defined by Binley et al. (2021), is any research where members of the public are actively involved in either the collection or analysis of data or samples. Examples of community science programs whose aim is to monitor rare plants include the Custodians of Rare and Endangered Wildflowers in South Africa (CREW: https://www.sanbi.org/biodiversity/building-knowledge/biodiversity-monitoring-assessment/custodians-of-rare-and-endangered-wildflowers-crew-programme/), the FLORON Plant Atlas in the Netherlands (https://www.floron.nl/about-us), and the Plants of Concern program in the United States (POC: https://plantsofconcern.org/). Other examples of community science programs for rare plant conservation involve the use of apps such as iNaturalist (Gaier & Resasco, 2023; Henning et al., 2023) and social media platforms such as Facebook (Marcenò et al., 2021).

Remote sensing involves acquiring information about species at a distance, for example, using satellites or aircraft (Canada Centre for Remote Sensing, n.d.). Remote sensing can be classified into two categories: direct remote sensing and indirect remote sensing. For the purposes of this review, we focused on direct remote sensing. As defined by Cerrejón et al. (2021), direct remote sensing is the use of remote sensing technologies for the detection of species, species assemblages, or ecological communities. Direct detection can be carried out in two ways: visual identification and image classification. Visual identification involves directly observing the target species and identifying it based on its physical characteristics. Image classification involves distinguishing species by their spectral features. Direct remote sensing differs from indirect remote sensing in that the indirect approach is used to infer species' habitat preferences or predict species distributions, rather than to detect species. Examples of direct remote sensing for rare plant detection include the use of drones to detect an endemic species via visual identification (Rominger & Meyer, 2019) and the use of satellite imagery to detect endangered tree species via spectral features (Omer et al., 2015).

eDNA, as per Taberlet et al. (2012), is DNA that can be extracted from environmental samples (e.g., soil, water, or air) without first isolating any target organisms. Examples of the use of eDNA for rare plant detection include designing surveys for detecting orchids that survive below ground for long periods of time (Hartvig et al., 2021) and using DNA from pollen grains for detecting plant species composition (Leontidou et al., 2021).

Our objective was to construct an evidence map to provide the current state of knowledge about the use of community science, direct remote sensing, and eDNA for the detection of rare terrestrial vascular plants. An evidence map is a systematic search of a broad field to provide a description of the available evidence base. The aims of an evidence map are not to provide a quantitative or qualitative answer to a question of intervention effectiveness or test a hypothesis. Instead, these mapping exercises are highly useful for the research and practice communities by providing descriptions of patterns in study methods and settings, and to identify knowledge gaps and future research needs (Haddaway et al., 2016; Miake-Lye et al., 2016). To our knowledge, this is the first evidence map examining this body of literature. We were interested in answering three questions: (1) What species have been detected with each technique? (2) What are the characteristics of these species? and (3) In what habitats have these techniques been used? After exploring these questions, we used a case study of species listed under at-risk categories as per the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) to find if there were species with similar characteristics that could potentially be detected via community science, direct remote sensing, and environmental DNA. To help inform the selection of appropriate monitoring techniques, we also discuss common problems found with these techniques and potential solutions to help overcome them, as well as sources of false negative and false positive errors and financial cost considerations for each technique.

To address these questions, our evidence map was based on the following study components:

- Population (study subject): rare terrestrial vascular plants
- Intervention (survey technique): community science, direct remote sensing, and environmental DNA
- Outcome: species detection

2 | METHODS

Our evidence map methodology was based closely on the recommendations outlined by the Collaboration for

Environmental Evidence (CEE, 2022) and conforms to ROSES reporting standards (Haddaway et al., 2018) for transparency and repeatability.

2.1 | Searching for articles

We conducted literature searches in February 2022 using Web of Science Core Collection accessed from Carleton University's institutional subscription and Google Scholar. We developed a list of potentially relevant search terms broken down into population, intervention, and outcome terms. We then developed a set of search strings and tested them for their comprehensiveness against a list of benchmark papers (Appendix S1) that had been previously identified as relevant for this evidence map. The search strings were refined iteratively, evaluating the sensitivity of the search terms and wildcards used. Search terms both in Web of Science Core Collection and Google Scholar were limited to English language due to project resource limitations; however, no language restrictions were applied during the searches. All articles found in Web of Science Core Collection were exported into EPPI-Reviewer Web (Thomas et al., 2022) for screening. Prior to screening, duplicates were identified and removed. We also issued a call on social media platforms (Twitter, Facebook) in February–March 2022 to find gray literature sources (i.e., academic theses, government/consultant/NGO reports), but no records were identified via this method.

The search in Web of Science Core Collection consisted of a single string broken down into population, intervention, and outcome terms. The search in Google Scholar consisted of a set of 12 strings with a different combination of population, intervention, and outcome terms. For each Google Scholar string, we captured the first 50 results (as in Roe et al., 2014; Hughes et al., 2014), this resulted in 600 records for screening. Both search strings were designed to ensure benchmark papers were captured and to be as comprehensive as possible within resource limitations (see Appendix S2 for details on search strings).

2.2 | Article screening and study eligibility criteria

2.2.1 | Screening process

We screened articles found in Web of Science Core Collection and Google Scholar at two distinct stages: (1) title and abstract; and (2) full text. Title and abstract screening was performed in EPPI-Reviewer software (Thomas et al., 2022), and full-text screening was done in Microsoft Excel. Prior to screening articles at each stage, we performed consistency checks (Appendix S3) and discussed discrepancies to ensure that consistent and repeatable decisions were being made by reviewers. We made attempts to retrieve missing articles by requesting them via Carleton University's Interlibrary Loans.

2.2.2 | Eligibility criteria

Articles were screened according to the eligibility criteria outlined in Table 1. Articles were only included if all criteria were met.

2.3 | Data coding strategy

After full-text screening, we proceeded to metadata extraction of the included articles. Each row in the metadata extraction codebook was classified by article, study, and dataset. We included peer-reviewed articles based on field data analysis, as well as management reports, conference proceedings, theses, and preprints. Studies were defined as independent experiments reported within an article (i.e., experiments that took place at a specific location and/or time period, not replicates within an experiment). Datasets were defined as the list of species studied (i.e., rare terrestrial vascular plants).

We identified articles that reported data found in other articles and combined them with the most complete source to avoid double counting the same datasets. The most complete source was considered the primary article, and the other articles were considered as supplementary material (e.g., a conference proceeding containing the same dataset as a published article was considered as supplementary material of the published article; articles derived from an original dataset expanding on the original study were considered as supplementary material of the original study).

We identified the following variables of interest through discussions with the review team and scoping exercises: (1) bibliographic information; (2) study location (e.g., country, ecoregion, biome, habitat); (3) target species characteristics (e.g., scientific name, common name, life form, conservation status); (4) detection technique (e.g., characteristics of community science, direct remote sensing, and eDNA methodologies); (5) study design (e.g., result validation with field surveys). We added new categories and options in an iterative process as data extraction proceeded.

In most cases, we extracted data based on author-reported information, although we used additional

TABLE 1 Article eligibility criteria.

Included	Excluded
Population (study subject): rare terrestrial vascular plants	
Any vascular plant that (i) Meets Rabinowitz (1981) definition of rarity, including endemic and threatened species. The paper or its supplementary material explicitly mentions that the species is rare, endemic, a habitat specialist, scarce, or threatened at any level (i.e., local, provincial, national, international) or the species has an endangered IUCN status. AND (ii) Lives in or on the ground, including helophytes and species living in vernal pools.	Any other taxa including: (i) Common plants used as proxies for rare plants. (ii) Invasive species when they are at their earliest stages of invasion. (iii) Rare plants that existed in the past and are now extinct. (iv) Plants that are now rare but were common when the study took place.
Intervention (survey technique): community science, direct remote sensing, environmental DNA	
(i) Any study that meets Binley et al. (2021) definition of community science. Including any study where participants detect real, artificial, decoy, and/or tagged plants. OR (ii) Any direct remote sensing study that meets Cerrejón et al. (2021) definition of direct remote sensing. OR (iii) Any environmental DNA study that meets Taberlet et al. (2012) definition of eDNA.	(i) Any study that uses other methods for species detection. (ii) Any study that does not meet the community science, direct remote sensing, or eDNA definitions. Including: • Community science studies in which participants are asked if they recognize a species, showing them pictures / herbaria; or in which participants participate in ethnobotanical studies; or in which participants are exclusively trained botanists. • Remote sensing studies that present habitat suitability or species distribution models (a.k.a. indirect remote sensing). • Environmental DNA studies where there is no direct evidence of the presence of a target species (e.g., metabarcoding for assessing species diversity without identifying the species).
Outcome: species detection	
Any study that: (i) Confirms the presence of a target species either at individual level or at population level. (ii) Attempts to detect a target species but fails.	Any study that: (i) Aims to detect plants to genus, family or other higher levels unless the sole member of a genus happens to be a target species.
Study design	
Any study that: (i) Is primary research carried out either in a natural or in an urban environment. (ii) Is either an observational or an experimental study, as long as their goal is to detect a target species. Including: • Mesocosm experiments • Restoration experiments	Any study that: (i) Proposes species detection via community science, direct remote sensing, or environmental DNA as potential next steps. (ii) Is a simulation of species detection that is not based on field data. (iii) Is secondary research (i.e., a review).
Language	
Texts written in English, French or Spanish.	Texts written in other languages.

sources for the following cases: (1) we identified ecoregions and biomes where studies took place using the Ecoregions 2017 map produced by Olson et al. (2001) and revised by Dinerstein et al. (2017) (https://ecoregions.appspot.com/); (2) we updated species' scientific names and extracted information on plant life form using the Plants of The World Online Database (https://powo.science.kew.org/); (3) we used the IUCN Red List database as of 2022 (https://www.iucnredlist.org/) for checking species conservation status.

We extracted information about the habitats where the studies took place, based on details reported in the articles. We then classified the habitats into seven categories based on their characteristics, following the IUCN Red List Habitats Classification Scheme (Version 3.1) (https://www.iucnredlist.org/resources/habitat-classification-scheme). The seven habitat categories were: closed (e.g., forests), semi-open (e.g., shrublands, grasslands, savannas, wetlands, marine coastal/supratidal areas, mires, heaths), open (e.g., deserts, rocky areas, marine intertidal areas, cliffs, sandbars, volcano craters), multiple (e.g., studies

that took place in areas containing a combination of open, semi-open, or closed habitats), urban (e.g., street trees, urban parks), other (e.g., agricultural lands, pastures), and unclear (e.g., unretrievable, unknown).

Critical appraisal (assessment of reliability and risk of bias in individual studies) is generally not included in evidence maps given the challenge of assessing study validity for the broad topic being described (CEE, 2022). If a study validity assessment is included, it is typically restricted to broad aspects of internal validity (Haddaway et al., 2016). In keeping with this practice, we did not examine the robustness or efficiency of the techniques used to detect rare plants, but rather described the distribution of research effort and identified potential knowledge gaps (i.e., areas that would benefit from further primary research) and knowledge clusters (i.e., subtopics that have a higher frequency of studies and that might warrant deeper synthesis). We did so by gathering information on whether field surveys were conducted in addition to the survey techniques used. We also examined whether articles that conducted field surveys compared the results with those of community science, direct remote sensing, and eDNA surveys. This involved comparing the number of species found, the number of individuals per species found, the time spent / area covered / financial resources used in each survey, or detection / misidentification rates.

2.4 | Data mapping

We created the metadata extraction codebook in Microsoft Excel and provided the key characteristics of the studies found on the use of community science, direct remote sensing, and eDNA for the detection of rare terrestrial vascular plants (Appendix S4). We used descriptive statistics to describe key variables, summarizing information in figures showing the distribution and frequency of the evidence base.

2.5 | Search for Canadian species at risk

We selected vascular plant species listed under at-risk categories (i.e., endangered, threatened, special concern species, Schedule 1) as per the COSEWIC on September 5, 2023.

To find species with similar characteristics to the ones found in the evidence database, we classified all species according to their life form using Kew Gardens Plants of the World Online Database (https://powo.science.kew.org/). We extracted information about the species' habitats from the COSEWIC status reports, and we coded that information according to the seven habitat categories specified in Section 2.3. For the list of species found, their life forms and habitats, see Appendix S5.

3 | RESULTS

3.1 | Literature searches and screening

The searches in Web of Science Core Collection and Google Scholar yielded 5037 articles, of which 255 were identified as duplicates and removed from the screening process. This resulted in 4782 articles for title and abstract screening. Of the 4782 articles screened at title and abstract, 4455 were excluded, yielding 327 articles for full-text screening. Of these articles, two were not retrievable through Carleton University subscriptions or Interlibrary Loans. Full-text screening removed 241 articles. Most of the articles were excluded because of an irrelevant population (e.g., article did not study any rare terrestrial vascular plant species), an irrelevant intervention (e.g., article did not comply with the community science, direct remote sensing, or eDNA technique definitions), or study design (e.g., article was not primary literature based on field data). A total of 86 articles were initially included for data extraction. We excluded 26 articles at this stage mainly because of irrelevant population, intervention, or study designs. This resulted in 92 studies from 60 articles included in the evidence map after metadata extraction (see Appendix S6 for ROSES flow diagram of inclusion/exclusion process results). A list of articles excluded at the full-text and metadata extraction stages along with reasons for their exclusion can be found in Appendix S7. Of the 60 articles included for final metadata extraction, most of the studies used direct remote sensing as their detection technique (42 articles; 70%), followed by community science (11 articles; 18%), and eDNA (7 articles; 12%).

3.2 | Summary of the evidence base

3.2.1 | Publication trends

Article publication dates ranged from 1996 to 2021. Community science articles appeared in 1996, direct remote sensing articles in 2003, and eDNA articles in 2018. Overall, there is an increasing trend in the number of articles that use these techniques for rare plant detection; however, the number of articles per year fluctuates by detection technique (Figure 1).

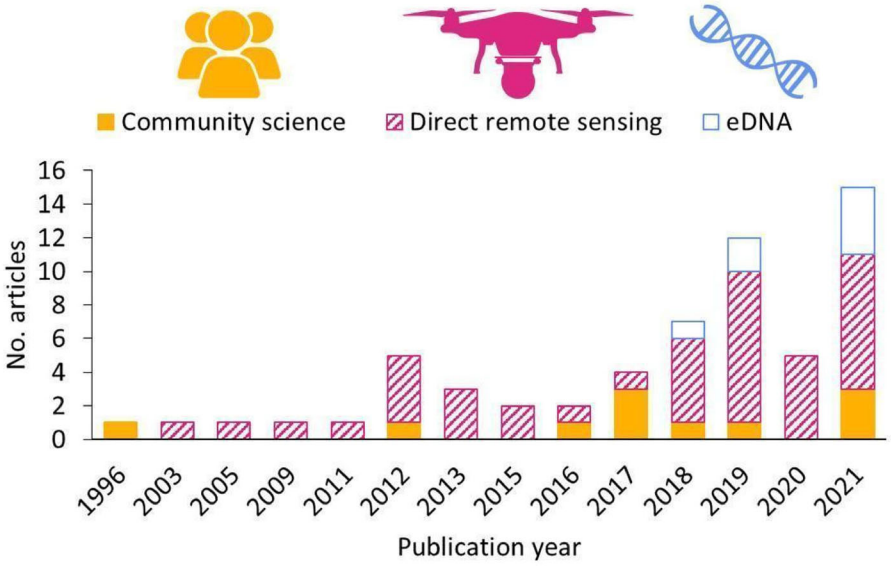

FIGURE 1 Number of articles found in this evidence map ($n = 60$) by publication year and survey technique. Community science (11 articles; 18%), direct remote sensing (42 articles; 70%), environmental DNA (7 articles; 12%). All vector images used in this figure and subsequent figures were obtained from https://svgsilh.com and have a Creative Commons License CC0.

3.2.2 | Study location

Despite the focus of our detailed search on North American species, studies included in this evidence map were conducted in 22 countries across all continents except for Antarctica. The country with the most studies was the United States (17 studies; 18%), followed by China (15%), and Australia and Norway (11% each) (Figure 2). Studies

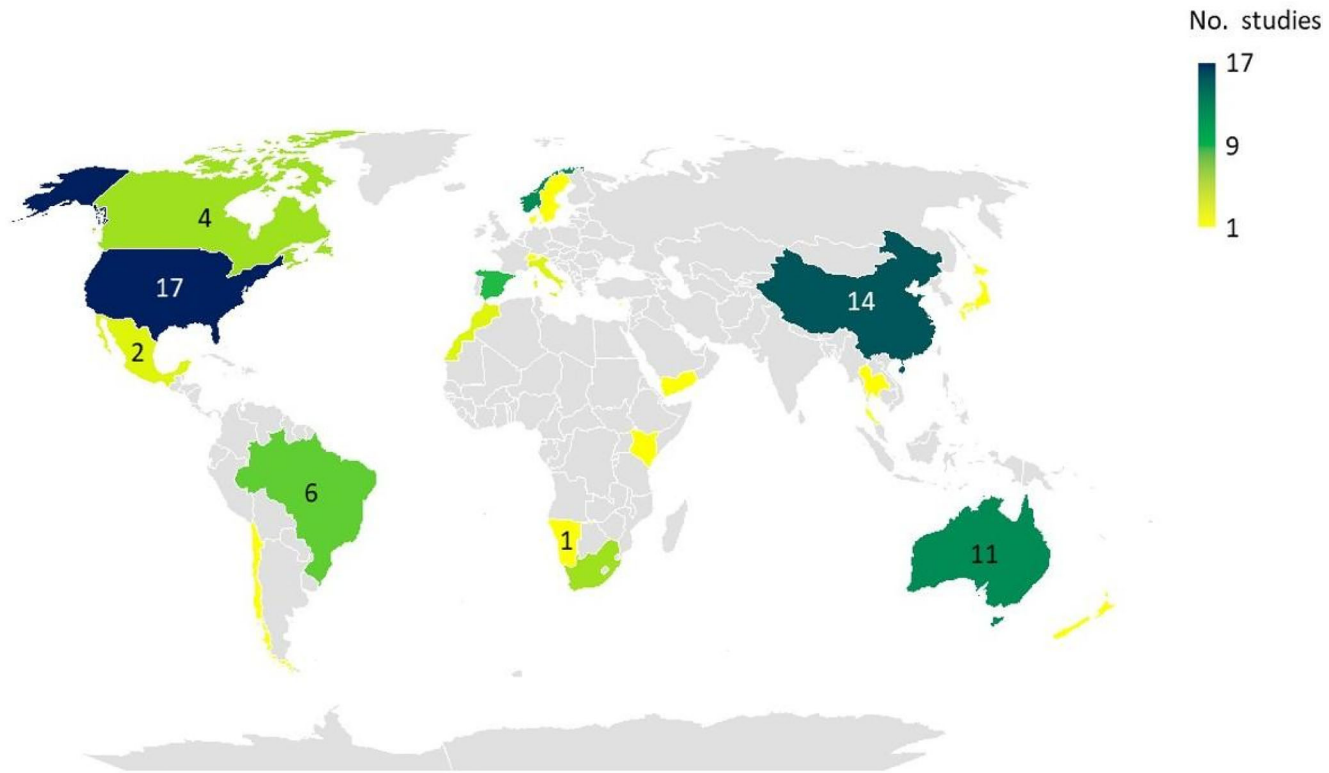

FIGURE 2 Geographic distribution of the included articles, displaying the number of studies per country. Map created in ArcGIS Pro Version 10.8.2 (Esri Inc., 2022).

took place in 11 unique biomes (Table 2) and 71 unique ecoregions (Appendix S8); some biomes and ecoregions were common to all three techniques.

3.2.3 | Species life form

Species detected in community science, direct remote sensing, and eDNA studies were classified into five life form categories: herbaceous species, shrub, tree, climber, or multiple. The multiple category was used when a species could adopt more than one life form.

The most frequent type of life form detected in community science studies was herbaceous species (186 species; 62%), while for direct remote sensing studies it was trees (30 species; 59%), and for eDNA studies it was herbaceous species (167 species; 71%) (Figure 3; see Appendix S9 for further summaries on life forms and species/family details).

TABLE 2 List of biomes where the studies for each survey technique took place.

Community science	Direct remote sensing	Environmental DNA
Mediterranean Forests, Woodlands & Scrub	Canary Islands dry woodlands and forests	Deserts & Xeric Shrublands
Temperate Broadleaf & Mixed Forests	Deserts & Xeric Shrublands	Mediterranean Forests, Woodlands & Scrub
Temperate Grasslands, Savannas & Shrublands	Mediterranean Forests, Woodlands & Scrub	Montane Grasslands & Shrublands
Tropical & Subtropical Moist Broadleaf Forests	Montane Grasslands & Shrublands	Temperate Broadleaf & Mixed Forests
	Temperate Broadleaf & Mixed Forests	Temperate Conifer Forests
	Temperate Grasslands, Savannas & Shrublands	Temperate Grasslands, Savannas & Shrublands
	Tropical & Subtropical Dry Broadleaf Forests	Tropical & Subtropical Dry Broadleaf Forests
	Tropical & Subtropical Grasslands, Savannas & Shrublands	Tundra
	Tropical & Subtropical Moist Broadleaf Forests	
	Tundra	

3.2.4 | Species conservation status

Only 193 species (33% of the total number of species) had an IUCN status. The most frequent conservation status was least concern (128 species; 66% of species with an IUCN status), followed by vulnerable (9%), near threatened (8%), endangered (7%), and critically endangered (5%). Seven species (4%) were reported as data deficient, and one species was classified as extinct in the wild (*Brugmansia arborea*).

3.2.5 | Species habitats

Most community science studies took place in urban settings (17 studies; 65%), while most direct remote sensing studies took place in study areas that comprised multiple habitats (13 studies; 30%), and most eDNA studies took place in semi-open habitats (10 studies; 45%) (Figure 4; see Appendix S8 for detailed breakdown of habitats).

3.2.6 | Study design

The following percentages of articles conducted field surveys in addition to the survey technique used: 64% for community science, 55% for direct remote sensing, and 86% for eDNA. For the community science articles that conducted field surveys, 71% made a comparison of survey results, while that percentage was 30% for direct remote sensing and 83% for eDNA articles.

3.2.7 | Canadian species at risk case study

We found a total of 183 species listed under an at-risk category in COSEWIC. Among them, 47 were listed as special concern (42 herbaceous species, 4 shrubs, 1 tree), 42 as threatened (1 climber, 33 herbaceous species, 6 shrubs, 2 trees), and 97 as endangered (89 herbaceous species, 1 shrub, 7 trees). Three species, *Psilocarphus brevissimus*, *Rotala ramosior*, and *Solidago speciosa*, were classified into multiple at-risk categories based on the status of their respective subpopulations. The most common habitat type was semi-open (123 species; 67%), followed by closed (15%), multiple (12%), and open (6%).

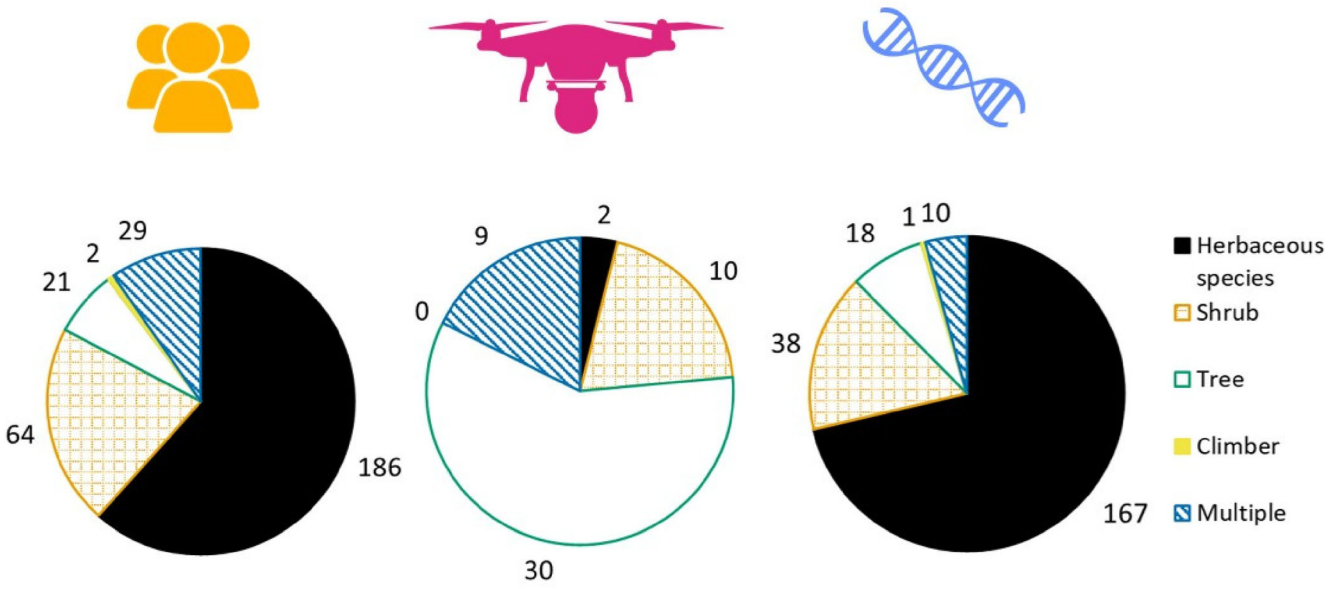

FIGURE 3 Number of species detected in the articles captured in this evidence map per survey technique and life form. Definitions of species life form categories can be found in Appendix S9b.

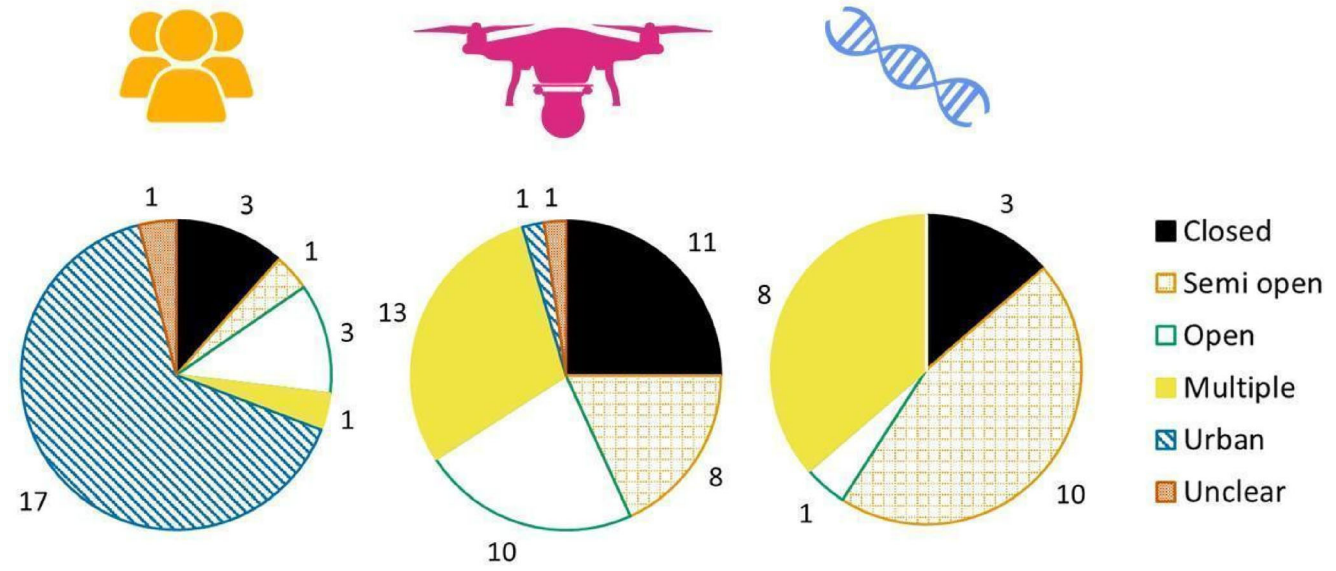

FIGURE 4 Number of studies in the articles captured in this evidence map per survey technique and habitat category.

4 | DISCUSSION

4.1 | Limitations of the map

4.1.1 | Limitations of the map due to the search strategy

Searches were only conducted using English search terms; it is therefore possible that the literature on the use of community science, direct remote sensing, and eDNA techniques for detecting rare terrestrial vascular plants is broader than the evidence captured here. Three articles could not be screened because they were written in Portuguese, German, and Chinese. However, a Spanish-language article that was found with English search terms was included in this map.

It is important to note that in this evidence map we used Rabinowitz's (1981) definition of a rare species. Therefore, species classified as rare following other frameworks such as Crisfield et al. (2024) or Violle et al. (2017) might not be captured in this evidence synthesis.

4.1.2 | Limitations of the map due to the evidence base

A quantitative analysis comparing the efficiency of each technique is not yet possible given that the evidence base is small, and the detection techniques are still relatively novel. This is especially true for eDNA since the evidence base from our search only dates from 2018, and the relatively large number of species (234) was contained in relatively few (7) articles.

In addition, the information reported in each article, even if using the same detection technique, varied greatly. Some articles did not provide any descriptions of the species they found, especially if they detected hundreds of species. Therefore, although we were able to identify those species as rare, we often did not have information about their threats. We also often did not find information on species abundance, which is an important factor in the detectability of a species. In the case of remote sensing and environmental DNA, it is sometimes not possible to estimate abundance. For example, remote sensing can be used to segment the crowns of trees, but some trees can have more than one crown; therefore, estimating abundance can be challenging. Similarly, while the concentration of eDNA can correlate positively to abundance, it can also correlate with biomass, and it might change depending on how eDNA is shed to the environment and how that eDNA is transported or degraded (Goldberg et al., 2016).

4.2 | Characteristics of species found with community science, direct remote sensing, and environmental DNA

Herbaceous species were the most common species in community science and eDNA studies, while trees dominated direct remote sensing studies. There was a general lack of studies for the detection of climber plants in all three techniques. These results may reflect the relative contribution that each life form makes to global biodiversity, since herbaceous species contribute approximately 32% and climbers 5% (Taylor et al., 2023). Regarding the high proportion of tree species in direct remote sensing studies, our results are consistent with those of Cerrejón et al. (2021), who also found that the most common type of rare plant found via direct remote sensing was trees. However, detecting herbaceous species via direct remote sensing is possible, even if a high spatial resolution is needed to achieve optimal results. For example, Rominger and Meyer (2019) used drones to detect dwarf bear-poppy (*Arctomecon humilis*) in the Mojave Desert (USA). In general, species detected via direct remote sensing techniques often exhibited distinct morphologies and/or high contrast with the background vegetation.

Most community science studies took place in urban areas, likely because those areas were more easily accessible to the public. This result is consistent with Soroye et al. (2022), who found that most iNaturalist records for threatened species came from urban and cropland/pasture environments. Many direct remote sensing studies took place in areas containing multiple habitat types, possibly because some of these studies covered large areas, such as entire islands or states. However, there was almost an equal number of direct remote sensing studies in open and closed habitats. Although visibility tends to be higher in open habitats, direct remote sensing studies can still be used in forests if appropriate conditions are met. For example, Leduc and Knudby (2018) used drones to detect patches of wild leek (*Allium tricoccum*) under the forest canopy shortly after snowmelt, when branches of trees were still bare. However, we classified all forests as closed habitats, and some forests may be more open than others. Regarding eDNA studies, most took place in semi-open habitats, such as wetlands and shrublands. We could not determine whether some habitats are more suitable than others for conducting eDNA surveys, as eDNA studies in terrestrial ecosystems are scarce, and many factors, such as DNA-substrate interactions, can greatly influence detection rates (Hassan et al., 2022).

4.3 | Potential Canadian species at risk that could be detected via community science, direct remote sensing, and environmental DNA

Species suitable for detection via community science are those easily distinguishable from similar species, found in publicly accessible areas, and resilient to disturbance or harvesting (Soroye et al., 2022). Our evidence map found that the most frequently detected species by community science were herbaceous species that can live in urban habitats. Based on these characteristics, some examples of Canadian species at risk that might potentially benefit from being detected via this technique are thread-leaved sundew (*Drosera filiformis*), showy phlox (*Phlox speciosa*), and soapweed (*Yucca glauca*). Although these species do not live in urban areas, they live in proximity to urban areas and hiking trails, have few lookalike species, and have a showy morphology.

Direct remote sensing may be a useful technique for detecting trees or shrubs, as well as a limited number of herbaceous species based on their unique visual characteristics or spectral signatures (Cerrejón et al., 2021). Some examples of Canadian at-risk trees that might

TABLE 3 Potential problems and possible solutions when conducting community science, direct remote sensing, and environmental DNA surveys for rare plant detection.

Potential problem	Possible solutions
Community science	
Poaching	Remove detailed locations of sensitive species from publicly-available data (Tulloch et al., 2018). Ask volunteers to sign a confidentiality form prohibiting disclosure of rare species locations, including on social media.
Disturbance	Limit participants in structured programs. Omit specific locations for popular entries that are likely to attract unmanageable attention (e.g., photogenic perennials). Promote best practices to minimize disturbance (Soroye et al., 2022).
Invasive species spread	Ask participants to use sanitation measures (e.g., removing mud from shoes).
Direct remote sensing	
Target species lives under the canopy	Survey when habitat becomes less dense (e.g. pre-leaf-out in a deciduous forest, Leduc & Knudby, 2018). Use LiDAR in combination with passive sensors (Hernandez-Santin et al., 2019).
Cryptic species	Survey when species has highest contrast with background vegetation. Use imagery with very high spatial resolution (Cerrejón et al., 2021).
Proximity to endangered birds [Only applicable to UAVs]	Survey when birds are least active, program a slow flight at higher altitude (de Leija et al., 2023).
Meteorological conditions prevent species detection	Survey at solar noon or on overcast days to minimize shadows in UAV imagery. Alternatively, survey both before and after solar noon to capture divergent shadow orientations, and edit orthomosaics (Rahman et al., 2019). For satellite imagery, exclude cloudy images (Li et al., 2022).
Environmental DNA	
Species lives in a hot and/or humid environment—eDNA degrades more quickly (Strickler et al., 2015)	Sample more frequently. Preserve samples quickly (e.g., filter water samples in the field/immediately upon return). Carefully storage samples (e.g., store samples under chilled and dark conditions to avoid DNA loss; Curtis et al., 2021).
Species has low abundance—eDNA is less abundant in the environment	Collect more samples. Carefully consider DNA storage and extraction techniques to maximize detectability (García et al., 2024; Renshaw et al., 2015). Process samples with highly sensitive techniques (e.g., qPCR and ddPCR).
Species eDNA has low dispersal capability	Collect more samples and sample at peak DNA shedding events (e.g., pollen production).
Lack of reference library for target species	Create a reference library from sample or museum specimens.
Lack of local sample vouchers—ambiguous identification if local population genetically different	Incorporate sequences of local samples and use a multi-locus approach (Espinosa Prieto et al., 2023).

potentially benefit from being detected via this technique are blue ash (*Fraxinus quadrangulata*), eastern flowering dogwood (*Cornus florida*), butternut (*Juglans cinerea*), and whitebark pine (*Pinus albicaulis*). These species are suffering severe declines due to invasive species and diseases. Additionally, herbaceous species such as eastern prickly pear cactus (*Opuntia humifusa*) and Yukon wild buckwheat (*Eriogonum flavum var. aquilinum*) might also be detected using this non-invasive approach.

DNA in eDNA samples is often degraded, diluted, and mixed with the DNA of non-target organisms (Taberlet et al., 2018). In addition, understanding the persistence of DNA over time or its mobility across space is important for interpreting the results of eDNA surveys (Taberlet et al., 2018). Despite these challenges, eDNA may offer advantages over field surveys by detecting cryptic or elusive species and aiding in uncertain taxonomic identification (Ruppert et al., 2019). Some examples of Canadian at-risk species that might potentially benefit

TABLE 4 Potential sources of false negatives and false positives for community science, direct remote sensing, and environmental DNA surveys.

Community science	
False negatives	Species present but undetected due to: Unavailability (e.g., the species was belowground at survey time or masked by other vegetation/objects). Inconspicuousness (e.g., species did not draw surveyor attention). Insufficient area coverage (e.g., surveyor did not pass near species). Misidentification (e.g., surveyor incorrectly identified species).
False positives	Species presence erroneously assumed due to a misidentification error.
Direct remote sensing	
False negatives	Species present but undetected due to: Unavailability (e.g., belowground or masked). Lack of distinctive features (e.g., no flowers for identification). Poor contrast with surroundings. Insufficient spatial resolution. Inadequate spectral resolution.
False positives	Species presence erroneously assumed due to incorrect interpretation of imagery, either through machine learning algorithms or manual interpretation.
Environmental DNA	
False negatives	Species present but undetected due to: Sampling issues (e.g., DNA of target species not collected or very degraded). Assay limitations (e.g., assay had low sensitivity or inhibitors in PCR reaction prevented amplification of target DNA sequence, see Thalinger et al. (2021) for recommendations on assay validation). Data analysis issues (e.g., rare sequence data, often discarded as errors, indicated presence of a species with either low DNA concentration in the environment, or poor amplification of its DNA). Incomplete reference database.
False positives	Species presence erroneously assumed due to: Lack of temporal information (e.g., species was present in the past and eDNA remnants suggest species is still present). Lack of spatial information (e.g., species doesn't live in the study area, but its DNA traveled there). Contamination during sample collection and processing. Lack of assay specificity (e.g., a sequence wrongly attributed to a species).

from being detected via this technique are phantom orchid (*Cephalanthera austiniae*), western prairie fringed orchid (*Platanthera praeclara*), and western spiderwort (*Tradescantia occidentalis*). The phantom orchid does not flower every year; the western prairie fringed orchid spends a significant portion of its life cycle underground as a tuber; and the western spiderwort flowers last only 1 day. All these species have genetic sequences registered at GenBank (https://www.ncbi.nlm.nih.gov/genbank/) that might be useful for identifying the species.

4.4 | Recommendations for future studies

Few articles discussed the efficacy of community science, direct remote sensing, and eDNA in detecting rare plants or how these techniques compare with traditional field surveys. However, information about technique robustness (e.g., detectability) or resources used (e.g., time, money) could be very useful for managers who are considering using these techniques for monitoring rare plant species.

For example, MacKenzie et al. (2017) analyzed misidentification rates between community science volunteers and professionals, investigating factors such as lookalike species, target species locations, and abundance to determine which species were more easily detected and correctly identified by volunteers. Rominger and Meyer (2019) calculated an identification confidence interval for a remotely sensed plant species based on the color, size, and shape of objects identified as plants in the images. Johnson et al. (2021) compared their eDNA metabarcoding survey results with two plant field surveys, examining total species detected, species overlaps between techniques, species characteristics, and data collection time.

Future studies could provide similar confidence levels of their results to assess technique robustness, even if broadly categorized as high, medium, or low. Additionally, tracking the time and resources used in data collection and processing is crucial for evaluating the strengths and weaknesses of different survey techniques. A study by Bennett et al. (2020) on the use of dogs for detecting rare species suggests a similar approach to evaluate technique efficacy. The authors suggest incorporating metrics such as precision, sensitivity, effort, and cost.

4.5 | Guidelines for using community science, direct remote sensing, and environmental DNA

Careful planning is necessary for applying any of these techniques for rare plant species detection. It is crucial to consider threats to the species, participant safety, and the

TABLE 5 Cost considerations for community science, direct remote sensing, and environmental DNA surveys.

Community science	
Start-up costs	Program management and communication (e.g., advertise community science event on social media). Interface software for users [if applicable].
Sample collection and processing costs	Liability insurance and safety training/equipment [if applicable]. Data curation by experts.
Direct remote sensing [only applicable to UAVs]	
Start-up costs	UAV equipment: UAV Cameras Batteries Chargers Ground control points Optional equipment [depending on survey needs]: Base station and rover for real-time kinematic (RTK) or post-processed kinematic (PPK) corrections. Precision global navigation satellite system (GNSS).
Sample collection and processing costs	Flight planning software. Safety equipment (e.g., fire extinguisher for LiPo batteries). Drone insurance. Optional equipment [depending on survey needs]: Power banks/generator to charge devices. Canopy to protect equipment. Take off and launch equipment.
Environmental DNA	
Start-up costs	Field equipment: Sampling equipment (e.g., waders, trowels, corers) Filtration device (e.g., syringe/peristaltic pump). Lab equipment: Separate rooms for DNA extraction and PCR amplification (see Goldberg et al. (2016), Table 2 for further recommendations) Positive air pressure room Biosafety cabinet with HEPA filter and UV light Centrifuge Vortex Incubator Pipettes Fridge (−20°C or −80°C, depending on needs).
Sample collection and processing costs	Field equipment: Consumables (e.g., sampling bottles/bags, gloves, masks, filters, cleaning supplies). Storage equipment (e.g., cooler/ethanol). Lab equipment: Consumables (e.g., pipette tips, tubes, gloves, masks, cleaning supplies). Assay preparation reagents (e.g., reagents used in the preparation of the reference library and the design and validation of primers and probes). DNA extraction/purification/amplification/sequencing reagents. Laboratory fees (e.g., private laboratory sequencing costs) Leasing costs (e.g., if using equipment from other institutions or conducting lab procedures in a specialized eDNA facility).

feasibility of the chosen technique based on the context. Table 3 outlines common problems associated with each technique and suggests potential solutions to help overcome them. This table is not exhaustive, since each survey presents its unique challenges. Some problems might be difficult or impossible to overcome; for example, some species hybridize, and one might only be able to identify them to genus or family level. Other problems are common to all three techniques and are unavoidable in conventional field surveys. For example, due to land or

airspace access restrictions, it may not be possible to survey some areas or access permits may be necessary. To better understand each technique's challenges, we recommend consulting experts and conducting pilot studies.

Apart from considering the challenges associated with each technique, it is important to remember that each technique has different sources of false negative and false positive errors. False negative errors occur when a species is present in the surveyed habitat at the time of the survey, but it is not detected and/or correctly identified. False positive errors occur when a species is not present in the surveyed habitat or at the time of the survey, but it is detected. Table 4 outlines common sources of false positive and false negative errors for each technique. While no technique is perfect at detecting species, these techniques can potentially complement each other and conventional field surveys to increase detectability rates and confidence in results.

Finally, one should consider the financial and logistical costs involved in the surveys. The financial costs can vary significantly, since each technique can adopt multiple potential workflows, and costs vary among workflows and study locations. As these techniques develop, costs may also change. Table 5 provides a list of cost considerations for each technique. All techniques can potentially incur additional costs such as training, transportation to study site(s), software licences, and purchase of high-performance computing infrastructure. To reduce costs and improve efficiency, we recommend collaborating with other researchers, institutions, and companies.

5 | CONCLUSION

Community science, remote sensing, and eDNA are increasingly being recognized for their potential in biodiversity monitoring. Despite the variation in species detectability among the survey techniques explored in this evidence map, community science, remote sensing, and eDNA could, in some cases, be used alongside traditional field surveys to increase the chances of detecting rare plants. Practitioners could use this evidence map database to filter articles based on the detection technique used, study location, habitat type, and/or plant life form to read specific details on how the studies were conducted. However, our evidence map highlights that these techniques have rarely been used to detect rare terrestrial vascular plants. There is a need to explore how these techniques complement each other and traditional field surveys. To fully realize the potential of these techniques in rare plant monitoring programs, future studies should focus on evaluating the accuracy and cost-effectiveness of these techniques in different contexts (e.g., spatial scales, target species, habitats). By addressing these aspects, researchers and managers could make more informed decisions about incorporating these novel techniques into biodiversity monitoring programs.

AUTHOR CONTRIBUTIONS

Conceptualization: Ana, Trina, Joseph. *Methodology*: Ana, Trina, Joseph. *Formal analysis*: Ana. *Data curation*: Ana, Matthew. *Writing original draft*: Ana. *Writing review and editing*: All. *Visualization*: Ana. *Supervision*: Trina, Joseph. *Project administration*: Ana. *Funding acquisition*: Joseph.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Article metadata extraction can be found in Supplementary Material.

ORCID

Ana Hernández Martínez de la Riva https://orcid.org/0009-0000-0249-6474

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