Vascular plant extinction in the continental United States and Canada

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/cobi.13621.

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Keywords: conservation, rarity, taxonomy, extinction rate, single-site endemics

Article Impact Statement: The number of presumed extinct plants from the continental United States and Canada is much greater than previously recognized.

Abstract: Extinction rates are expected to increase during the Anthropocene. Current extinction rates of plants and many animals remain unknown. This study represents the first effort to quantify extinctions among the vascular flora of North America north of Mexico since European settlement. We compiled data on apparently extinct species by querying plant conservation databases, searching literature, and vetting the resulting list with botanical experts. Because taxonomic opinion varies widely, we developed an Index of Taxonomic Uncertainty (ITU). The ITU ranges from A to F, with A indicating unanimous taxonomic recognition and F indicating taxonomic recognition by only a single author. The ITU allowed us to rigorously evaluate extinction rates. Our data suggest 65 taxa (51 species and 14 infraspecific taxa) representing 33 families and 49 genera of vascular plants have become extinct in our study area since European settlement. Seven of these taxa exist in cultivation but are extinct in the wild. We found most extinctions in western North America, but that disparity may reflect the timing of botanical exploration relative to settlement. Sixty-four percent of extinct plants were single-site endemics, and many occurred outside recognized biodiversity hotspots. Given the paucity of plant surveys in many areas of North America, particularly prior to European settlement, the actual extinction rate of vascular plants is undoubtedly much higher than indicated here.

Introduction

Much recent attention has been devoted to the rates at which plants and animals are going extinct (e.g., Pimm & Raven 2000; Ceballos et al. 2015; Pelletier et al. 2018; Humphreys et al. 2019.). Although we know that current extinction rates far surpass background rates (Pimm et al. 2014; Ladel 2019), quantifying extinctions is still critically important for improving accuracy of extinction estimates and predictions. Reliable information on extinction, threats, and recovery will help conservation practitioners be more effective at preventing extinctions. Some 450,000 species of vascular plants are extant globally, ca. 3.5 times the number of vertebrate species (Pimm & Joppa 2015; Ceballos et al. 2018). Because plants serve as the foundation for most terrestrial ecosystems, documenting plant extinctions is an urgent need.

Plant extinctions have been analyzed globally (Pelletier et al. 2018; Humphreys et al. 2019) and for California (Rejmánek 2018). However, a detailed analysis of plant extinctions has not been conducted for North America. Here we present a thorough analysis of the extinct vascular plants of North America north of Mexico (hereafter North America), which includes the contiguous United States, Alaska, and Canada, based on literature review, herbarium research, and fieldwork. These data on extinct plants provide a baseline for monitoring extinctions during the Anthropocene (Walters et al. 2016) and will improve assessment of extinction rates over time.

Methods

We created our list of presumably extinct plants from numerous sources starting with recent literature (e.g., Flora of North America, state and regional floras, and monographs). We vetted these data with conservation databases (e.g., NatureServe Explorer and Jepson eFlora). Lastly, we consulted regional experts to assess the taxonomic merit and the extinction status of the list.

To evaluate which published names represent meritorious taxa, we developed an Index of Taxonomic Uncertainty (ITU), a new method to determine scientific consensus on a taxon. Publications on species' extinctions typically reference a single taxonomic authority, largely omitting discussion of taxonomic uncertainty (Ceballos et al. 2015; Pelletier et al. 2018; Humphreys et al. 2019; Le Roux et al. 2019). Yet taxonomic uncertainty is critically important for putatively extinct taxa. Extinct taxa have higher levels of taxonomic uncertainty than extant taxa because researchers are not able to conduct robust genetic research from very small samples often limited to herbarium specimens rather than live plants.

To calculate the ITU, we vetted each name by reviewing the literature, mostly monographic and floristic treatments, in which each taxon was critically evaluated against other related taxa by an expert. We did not use taxonomic databases to calculate the ITU because these often reflect other published literature rather than novel taxonomic evaluations. If authors of consulted literature universally accepted a taxon as a distinct entity, regardless of taxonomic rank, it received a score of A. If a taxon was placed in synonymy by some authors but the majority recognized it as distinct, it received a score of B. If the name was usually placed in synonymy but numerous treatments still recognized the taxon as valid, a score of C was applied. Scores of D and F were applied if a taxon was rarely recognized (i.e., <85% of the time) or never recognized after initial publication of the name, respectively. If a name did not appear as a recognized taxon in a floristic work and was not listed in synonymy, the source was not used in the ITU calculation. For this analysis we include extinct taxa with ITU's of A, B, or C. Taxa with scores of D and F were excluded but can be found in Supporting Information.

To determine if taxa should be assigned a conservation status of extinct, we followed NatureServe methodology (Faber-Langendoen et al. 2012), the North American standard, because most North American plants (species and infraspecies) have been assessed at least once. The IUCN Red List of Threatened Species (hereafter Red List), the international standard, includes assessments for less than 20% of North American plants (species only). NatureServe assessments use Presumed Extinct (GX for species; TX for infraspecies) and Possibly Extinct (GH or TH) whereas the Red List uses Extinct (EX) and Critically Endangered (Possibly Extinct). For both systems, categories are based on previous survey effort and the likelihood of rediscovery. Due to the high degree of uncertainty surrounding modern extinctions, we use the term ‘extinct’ for simplicity when discussing both categories.

Taxonomically meritorious taxa thought to be extinct were assessed using NatureServe’s Conservation Rank Calculator (NatureServe 2020) and taxa categorized as GX, TX, GH, or TH were considered extinct. The Red List currently identifies only 2 of our 65 extinct taxa as extinct, critically endangered (Possibly Extinct), or extinct in the wild (IUCN 2020). To further compare our results to the Red List, we assessed a subset of 11 extinct plants with the IUCN extinction assessment tool (Akçakaya et al. 2017; Keith et al. 2017; Thompson et al. 2017; IUCN 2020). These 11 were selected because they were well dispersed across the study area, represented a diversity of distributions (i.e., single site endemics vs. broad geographic ranges), and sufficient information was available to support assessment decisions.

Each extinct taxon was searched through the Botanic Gardens International Database (BGCI 2019) to determine if any institution reported having *ex situ* collections of extinct species. Positive findings were further vetted with each garden.

Results

Our data show 65 taxa (51 species and 14 infraspecific taxa) of vascular plants from North America have gone extinct or possibly extinct since European settlement (33 GX and 32 GH). The native flora of North America is ca. 15,882 taxa (USDA PLANTS Database 2020) yielding an extinction rate of 0.14 taxa/year or 1.4 per decade, using 1565 as the date of first European settlement (455 years). The extinct flora represents 0.004% of the total flora, and includes 5 small trees, 8 shrubs, 37 perennial herbs, and 15 annual herbs (Table 1). These extinctions represent 33 families and 49 genera (Table 1). Asteraceae (8), Fabaceae (7), Rosaceae (7), and Boraginaceae (6) have the most extinctions whereas Cyperaceae (1), Orchidaceae (1), and Poaceae (2) were poorly represented. The most impacted genera were *Crataegus* (4), *Astragalus* (3), *Cryptantha* (3), and *Plagiobothrys* (3). *Cryptantha* and *Plagiobothrys,* both in the Boraginaceae, represent all known extinctions for this family. This could have phylogenetic implications as *Cryptantha* and *Plagiobothrys* constitute much of the clade corresponding to subtribe Amsinckiinae (Simpson et al. 2017). The Supporting Information includes data on geographic locations of the extinct plants, date of last observation, life history, habitat, putative cause of extinction, family, whether the taxon was known only from the type, and general notes. The geographic data were used to create a map of extinct plants (Fig. 1).

Extinctions are heavily concentrated in the southwestern United States (Fig. 1). The U.S. states with the most extinctions are California (19), Texas (9), then Florida and New Mexico (4 each). Canada had a single extinction. The New England states had 5 extinctions, despite not being a biodiversity hotspot. Of the extinct taxa, 42 (64%) were apparently single-site endemics (having an extremely narrow and clustered distribution with an Area of Occupancy of ≤6, 1 km^2 grid cells). Twenty taxa (31% of the extinct plants) are known only from the type specimens. Since 1995, 4 extinct species from North America have been described as new to science from herbarium vouchers (Mosyakin 1995; Brown 2000; Johnston & Ertter 2010; Knapp et al. 2020).

We document 7 plants as extinct in the wild (EW), defined here as a species surviving only in cultivation (Table 1). Of the 7 EW plants, 4 were not previously recognized as such before this study. Two extinct plants are reported from *ex situ* gardens in the Botanic Gardens Conservation International Database (BGCI 2019); these identifications are yet to be confirmed by reporting institutions and are denoted as “EW?” (Table 1). Three additional species were reported from BGCI as having *ex situ* collections but communications with the reporting institutions revealed these to be misidentifications.

Forty-one taxa had ITUs of A, 14 of B, and 9 of C. A single taxon was so recently recognized as distinct that an ITU could not be calculated. An additional 80 taxa were determined to have ITUs of D or F.

Our Red List assessments resulted in all 11 taxa categorized as Extinct (EX) or Critically Endangered (Possibly Extinct) (CR(PE)). Comparing with NatureServe assessments, in most cases GX aligned with EX and GH aligned with CR(PE); however, in 2 cases the Red List category was EX while NatureServe's was GH. In the case of the two published Red List assessments, the NatureServe and Red List assessments aligned (Supporting Information).

Discussion

Extinction is difficult to prove, making determinations of what constitutes an extinct species uncertain (Diamond 1987). Rediscoveries of some taxa may occur. Each taxon reported here has been sought in the field, but not rediscovered. Our analysis shows previous analyses of plant extinction vastly underestimate the number of extinctions in North America.

Recent authors suggest nearly 600 plants have gone extinct globally, with 38 extinctions in 16 U.S. states (Humphreys et al. 2019). Knapp et al. (2020) disputed this estimate for North America based on the inclusion of 14 taxa that were either extant or too taxonomically dubious. Despite reducing the extinction estimate in Humphreys et al. (2019) by eliminating extant or dubious taxa, our data show a more dire situation, documenting 65 extinct taxa in 31 U.S. states, the District of Columbia, and Ontario. These results indicate that nearly twice as many taxa have gone extinct, over a much larger geographic area, than previously estimated.

The cause of any extinction is difficult to determine (Le Roux et al. 2019). Unless the species was a single-site endemic whose habitat was destroyed, the cause of an extinction is often hypothetical. Nevertheless, direct anthropogenic disturbances (i.e., habitat alteration or destruction) are the single largest contributor to extinction. Only two species in our dataset had broad geographic ranges (defined here as found in four or more states). The reasons for these extinctions are unknown but were likely multifaceted.

We suspect the actual number of extinct plants to be considerably higher than reported, but data limitations abound. Twelve species new to science are discovered each year, on average, in California alone (Ertter 2000), suggesting an untold number of plants went extinct before scientific discovery. Much of eastern North America was impacted by European settlement before botanical exploration began. Florida, with the highest concentration of endemic plants within the North American Coastal Plain biodiversity hotspot (Noss et al. 2015), likely lost many endemic plants before they were described. Our data document 4 extinct plants in Florida but it is unlikely that this hotspot would lose fewer plants than a less diverse area of similar size, such as New England (5 in our data).

The geographic distribution of extinctions is heavily concentrated in the southwestern United States (Fig. 1). Topographic, climatic, and habitat heterogeneity of the drier parts of the West is associated with a high diversity of narrow endemics that may be inherently vulnerable to extinction. However, we suspect the disproportionate number of extinctions in the southwestern U.S. cannot be explained solely as an artifact of biodiversity patterns. Compared to the eastern states, western states had much more botanical exploration before widescale settlement (McKelvey 1956; Lewis & Clark 2003). Nevertheless, some landscapes, such as large areas of California, underwent such extreme habitat transformation by invasive Eurasian grasses and forbs prior to careful botanical documentation that their pre-European condition is controversial (Minnich 2008).

Much remains to be learned in the developing scientific arena of extinction documentation. Extinct species are still being described from old herbarium specimens, underscoring the importance of continued documentation of the flora and support of museum collections (Bebber et al. 2010). Almost certainly, additional taxa will be described after they have gone extinct. Collection and sampling bias influences our knowledge of the extinct flora. The Cyperaceae, Orchidaceae, and Poaceae are among the most diverse families of plants, yet only 4 members of these families are known to be extinct from our study area. *Govenia floridana*, the only member of the Orchidaceae, was pushed to extinction by over-collecting (Gann 2002). Cyperaceae and Poaceae are notoriously under-collected and under-investigated.

The role of seed banks and botanical gardens in maintaining *ex situ* collections is of growing importance, as recognized by the Center of Plant Conservation and its partners (Miller et al. 2016). However, of the 7 EW taxa we document, the conservation value of 4 had not been recognized before this study. Without these gardens, these taxa would be extinct. To prevent future extinctions, the rarest plants should be prioritized for both *in situ* and *ex situ* conservation.

Preventing extinction is the lowest bar for conservation success, yet species still go extinct. Our results indicate 64% of extinct plants are historically known from only a single site or collection. Though determining whether an extinct species was a single-site endemic is problematic, as a single historical collection may not represent the total geographic range of a species, we argue that preventing further extinction requires prioritizing single-site endemics. Our preliminary data indicate 92 extant single-site endemic plants in North America (NatureServe 2020). Unfortunately, *in situ* conservation efforts have often moved away from small-site protection, despite recent analyses showing small, isolated patches are disproportionately important for biodiversity (Wintle et al. 2018). A renewed focus on conserving small sites, as a complement to landscape-level conservation, is needed if the goal is to prevent extinctions. Many factors are predicted to increase future extinction rates for rare plants, including climate change and accelerated land-use change resulting from human population growth (Enquist et al. 2019). With greater effort on *ex situ* and *in situ* conservation for rare plants, especially single-site endemics, many future extinctions might be prevented.

Acknowledgments

We thank the Smithsonian Institution, namely Robin Everly, for access to the library. Abby Meyer provided information from BGCI. We are indebted to Amanda Treher (NatureServe) for her time, attention to data quality, and updating the NatureServe database. We thank the following experts for comments on this manuscript or comments about taxonomic groups: Ihsan Al-Shehbaz, Adam Black, Patricia Dávila, Carolyn Ferguson, Aaron Floden, Art Gillman, Barbara Goettsch, Matt Guilliams, Raul Gutierrez, Jill Handwerk, Walter Holmes, Ron Lance, Matt Lobdell, Lucas Majure, Aaron Marcus, Joyce Maschinski, Jordan Metzgar, William Nichols, Susan Panjabi, Paul Peterson, James Phipps, Caroline Pollock, Jackie Poole, Mike Powell, Daniela Roth, Ed Schilling, Aaron Sims, Jim Solomon, Robert Soreng, the late Billie Turner, Murphy Westwood, Johnny Wilson, Michael Windham, and Theo Witsell. We thank Resit Akçakaya and Marcel Rejmánek for critical reviews that improved this manuscript.

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Table 1. Extinct plants of North America north of Mexico with extinction qualifier, taxonomic family, life history grouping, geographic distribution, and corresponding ITU Score.

Extinct Plants of North America north of Mexico

Scientific Name	Qualifier	Family	Life History	Distribution	NatureServe Rank	ITU
Y		Orobanchaceae	AH	LA	GH	A
Arctostaphylos franciscana Eastw.	EW	Ericaceae	S	CA	GHC	A
Astilbe crenatiloba (Britton) Small		Saxifragaceae	PH	TN	GX	B
Astragalus endopterus (Barneby) Barneby		Fabaceae	AH	AZ	GH	A
Astragalus kentrophyta A. Gray var. *douglasii* Barneby		Fabaceae	PH	WA	G5TX	A
Astragalus robbinsii (Oakes) A. Gray var. *robbinsii*		Fabaceae	PH	VT	G5TX	A
Atriplex tularensis Coville		Chenopodiaceae	AH	CA	GX	A
Blephilia hirsuta (Pursh) Benth. var. *glabrata* Fern.		Lamiaceae	PH	VT	G5TH	B
Boechera fructicosa (A. Nelson) Al-Shehbaz		Brassicaceae	PH	WY	GH	B
Brickellia chenopodina (Greene ex Wooton & Standl.) B.L.		Asteraceae	S	NM	GH	B

Rob.						
Brickellia hinckleyi Standl. var. *terlinguensis* (Flyr) B.L. Turner		Asteraceae	S/SS	TX	G2TH	A
Calochortus indecorus Ownbey & M. Peck		Liliaceae	PH	OR	GX	A
Calochortus monanthus Ownbey		Liliaceae	PH	CA	GX	A
Castilleja leschkeana J.T. Howell		Convolvulaceae	PH	CA	G5TX	B
Castilleja uliginosa Eastw.		Orobanchaceae	PH	CA	GX	C
Calystegia sepium (L.) R. Br. ssp. *binghamiae* (Greene) Brummitt		Orobanchaceae	PH	CA	G5TX	C
Cirsium praeteriens J.F. Macbr.		Asteraceae	PH	CA	GX	B
Corispermum pallidum Mosyakin		Chenopodiaceae	AH	WA	GH	A
Crataegus austromontana Beadle		Rosaceae	T	AL, TN	GH	B
Crataegus delawarensis Sarg.	EW?	Rosaceae	T	DE	GH	C
Crataegus fecunda Sarg.	EW	Rosaceae	T	AR, IL, KY, MO	GXC	B
Crataegus lanuginosa Sarg.	EW	Rosaceae	T	MO	GH	A
Cryptantha aperta (Eastw.) Payson		Boraginaceae	PH	CO	GH	A

Cryptantha hooveri I.M. Johnst.		Boraginaceae	AH	CA	GH	A
Cryptantha insolita (J.F. Macbr.) Payson		Boraginaceae	PH	NV	GH	B
Dalea sabinalis (S. Watson) Shinners		Fabaceae	PH	TX	GH	A
Digitaria filiformis (L.) Koeler var. *laeviglumis* (Fernald) Wipff		Poaceae	PH	NH	G5TH	B
Diplacus traskiae (A.L.Grant) G.L. Nesom		Phrymaceae	AH	CA	GX	A
Eleocharis brachycarpa Svenson		Cyperaceae	AH	TX & MX	GH	A
Elodea schweinitzii Casp.		Hydrocharitaceae	PH	NY, PA	GHQ	C
Erigeron mariposanus Congdon		Asteraceae	PH	CA	GX	B
Eriochloa michauxii (Poir.) Hitchcock var. *simpsonii* (Hitchc.) Hitchc.		Poaceae	PH	FL	G3G4TH	A
Euonymus atropurpureus Jacq. var. *cheatumii* Lundell	EW?	Celastraceae	S	TX	G5THQ	C
Franklinia alatamaha Marshall	EW	Theaceae	S	GA	GXC	A
Govenia floridana P.M. Br.		Orchidaceae	PH	FL	GX	A

Hedeoma pilosa R.S. Irving		Lamiaceae	PH	TX	GH	A
Helianthus nuttallii Torr. & A. Gray ssp. *parishii* (A. Gray) Heiser		Asteraceae	PH	CA	G5TX	A
Helianthus praetermissus E. Watson		Asteraceae	AH?	AZ?, NM	GH	C
Isocoma humilis G.L. Nesom		Asteraceae	PH or SS	UT	GH	A
Juncus pervetus Fernald		Juncaceae	PH	MA	GX	B
Lechea lakelae Wilbur		Cistaceae	PH	FL	GX	A
Lycium verrucosum Eastw.		Solanaceae	S	CA	GX	A
Marshallia grandiflora Beadle & F.E. Boynton		Asteraceae	PH	NC	GX	N/A
Micranthemum micranthemoides (Nutt.) Wettst.		Linderniaceae	AH	DC, DE, MD, NJ, NY, PA, VA	GH	A
Monardella leucocephala A. Gray		Lamiaceae	AH	CA	GX	A
Monardella pringlei A. Gray		Lamiaceae	AH	CA	GX	A
Narthecium montanum (Small) Grey		Nartheciaceae	PH	NC	GX	C
Orbexilum macrophyllum (Rowlee ex Small) Rydb.		Fabaceae	PH	NC	GX	A
Orbexilum stipulatum		Fabaceae	PH	KY	GX	A

(Torr. & A. Gray) Rydb.						
Paronychia maccartii Correll		Caryophyllaceae	PH	TX	GH	A
Plagiobothrys lamprocarpus (Piper) I.M. Johnst.		Boraginaceae	AH	OR	GX	A
Plagiobothrys lithocaryus (Greene ex A. Gray) I.M. Johnst.		Boraginaceae	AH	CA	GX	A
Plagiobothrys mollis (A. Gray) I.M. Johnst. var. *vestitus* (Greene) I.M. Johnst.		Boraginaceae	PH	CA	G4?TX	A
Polygonatum biflorum (Walter) Elliott var. *melleum* (Farw.) R.P. Ownbey		Asparagaceae	PH	MI, ON	G5TH	C
Potentilla multijuga Lehm.		Rosaceae	PH	CA	GX	A
Potentilla uliginosa B.C. Johnst. & Ertter		Rosaceae	PH	CA	GX	A
Proboscidea spicata Correll		Martyniaceae	AH	TX & MX	GH	B
Prunus maritima Marshall var. *gravesii* (Small) G.J. Anderson	EW	Rosaceae	S	CT	G4TXCQ	C
Quercus tardifolia C.H. Mull.		Fagaceae	T	TX & MX	GH	B
Ribes		Grossulariacea	S	CA	G5TX	A

divaricatum Douglas var. *parishii* (A. Heller) Jep.		e				
Rumex tomentellus Rech.f.		Polygonaceae	PH	NM	GH	A
Sesuvium trianthemoides Correll		Aizoaceae	AH	TX	GH	A
Sphaeralcea procera Ced. Porter		Malvaceae	PH	NM	GH	A
Tephrosia angustissima Shuttleworth ex Chap. var. *angustissima*		Fabaceae	PH	FL	G1TX	A
Thismia americana Pfeiff.		Burmaniaceae	PH	IL	GH	A

EW = Extinct in the wild, EW? = species reported as extant through Botanical Gardens Conservation International but whose identity could not be confirmed; Life History abbreviations are as follows: AH – Annual Herb, PH – Perennial Herb, S – Shrub (or SS – Subshrub), T –Tree; Distribution gives state or province abbreviations. ITU Score is the corresponding score for each taxon, ranging A–C.

Fig. 1. Map of extinct plants of North America north of Mexico. Dots = georeferenced specimen locations. Checkered polygons = broader ranging species.

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