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The impact of climate change on endangered plants and lichen

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Abstract

The Endangered Species Act (ESA) was a landmark protection for rare organisms in the United States. Although the ESA is known for its protection of wildlife, a majority of listed species are actually plants and lichen. Climate change will impact species populations globally. Already-rare species, like those listed in the ESA, are at an even higher risk due to climate change. Despite this, the risk climate change poses to endangered plants has not been systematically evaluated in over a decade. To address this gap, we modified previously existing qualitative assessment toolkits used to examine the threat of climate change in federal documentation on listed wildlife. These modified toolkits were then applied to the 771 ESA listed plants. First, we evaluated how sensitive ESA listed plants and lichens were to climate change based on nine quantitative sensitivity factors. Then, we evaluated if climate change was recognized as a threat for a species, and if actions were being taken to address the threats of climate change. We found that all ESA listed plant and lichen species are at least slightly (score of 1) sensitive to climate change, and therefore all listed plants and lichens are threatened by climate change. While a majority of ESA listing and recovery documents recognized climate change as a threat, very few had actions being taken in their recovery plans to address climate change directly. While acknowledging the threat that climate change poses to rare plants is an important first step, direct action will need to be taken to ensure the recovery of many of these species.

Introduction

Since the publication of Linnaeus' *Species plantarum* in 1753, over 600 plant species have become extinct globally [1, 2]. The true number is likely higher, as this estimate leaves out many plant groups that are data deficient, meaning that there is not enough known about these species to ascertain if they are threatened or at risk for extinction [3]. CO_2 emissions are the driving force of anthropogenic climate change and have been increasing in the earth's atmosphere since 1850. While the growth rate of CO_2 emissions has slowed in recent decades, total emissions overall continue to rise [4]. Likewise, while the historic background extinction rate for plant species has been estimated between .05 and .15 extinctions per 10,000 species per

100 years [5–9], the global extinction rate for plants under anthropogenic climate change may be as high as .6 species extinctions per 10,000 species per 100 years [10]. Given this raised risk of extinction, species already considered rare may be at an even higher risk to shifting climatic conditions [11]. Species with low population numbers are vulnerable to catastrophic events as well as the long-term impacts of Allee effects, which complicate long-term recovery of a species after a catastrophic event. Additionally, many rare species may be abundant, but geographically restricted, meaning a whole species could be impacted by a single catastrophic event [12]. Therefore, while many if not most plants will be impacted by climate change, it is particularly important to understand the impacts on rare plants, as their potential for recovery is far less likely.

Although ecosystems continue to be threatened by climate change, substantial conservation actions could help to mitigate its worst effects [4]. This study seeks to understand how the Endangered Species Act (ESA) directs conservation actions and establishes regulations to address the threat of climate change on listed plant and lichen species and to assess the actions, if any, being taken to mitigate climate change threats for those species. Understanding how the ESA addresses the threat of climate change for listed endangered species is vital to the persistence of these species into the future, as the populations of many endangered species are already dwindling. Through evaluations such as these, agencies such as the US Fish and Wildlife Service (US FWS) can have a better understanding of where they currently stand on incorporating climate change into conservation and recovery goals, and what can potentially be done to improve recovery plans and reviews. If the ESA is not directing conservation actions and regulation to climate change threats, then it is likely that, on a larger scale, ecosystems are also at risk and actions are not being taken to address these threats. Alternatively, if the ESA *is* integrating climate change into conservation actions and regulations and highlights actions needed to address climate change impacts for endangered plant species, then it could be used as a model for other climate and conservation-based initiatives elsewhere.

Climate change risks and plants

Climate change is predicted to impact a variety of global conditions, from shifting temperatures to changing precipitation patterns to sea level rise [4]. There has already been a 1.1˚C global temperature increase from 2011–2020 when compared to 1850–1900 averages [13] Changes in atmospheric CO_2 levels have been shown to alter vegetation functional groups [14, 15]. Increased temperatures have been shown to largely impact plant reproductive success, with warm temperatures accelerating phenological development, and heat stress leading to impaired fertilization and the abortion of plant reproductive organs [16, 17]. Rising temperatures have been linked to competitive displacement, predation intensification, and new predator-prey interactions. Alternatively, climate change may also allow for coexistence between species that was not possible under previous conditions [14]. Sea levels are also expect to rise globally as temperatures warm, leading to the erosion of key coast dune habitat for plant species, shifting nutrient availability and flooding stress for coastal plants, and along with the stress from flooding, often increased salinity, which some species are not able to tolerate [18–20]. All of these components have impacts on biotic factors and therefore may impact plants. Climate is a major factor in determining the distribution of species [21]. Under the pressure of climate change, the distributions of plant species could be altered in the future. Fig 1 illustrates how climate change may impact the United States through changing temperature and precipitation regimes, and shows the broad distribution critical habitats for endangered and threatened species across the United States. All regions of the United States will be impacted by changing climatic conditions, but the directionality and intensity vary depending on the region, as will the impacts on endangered species.

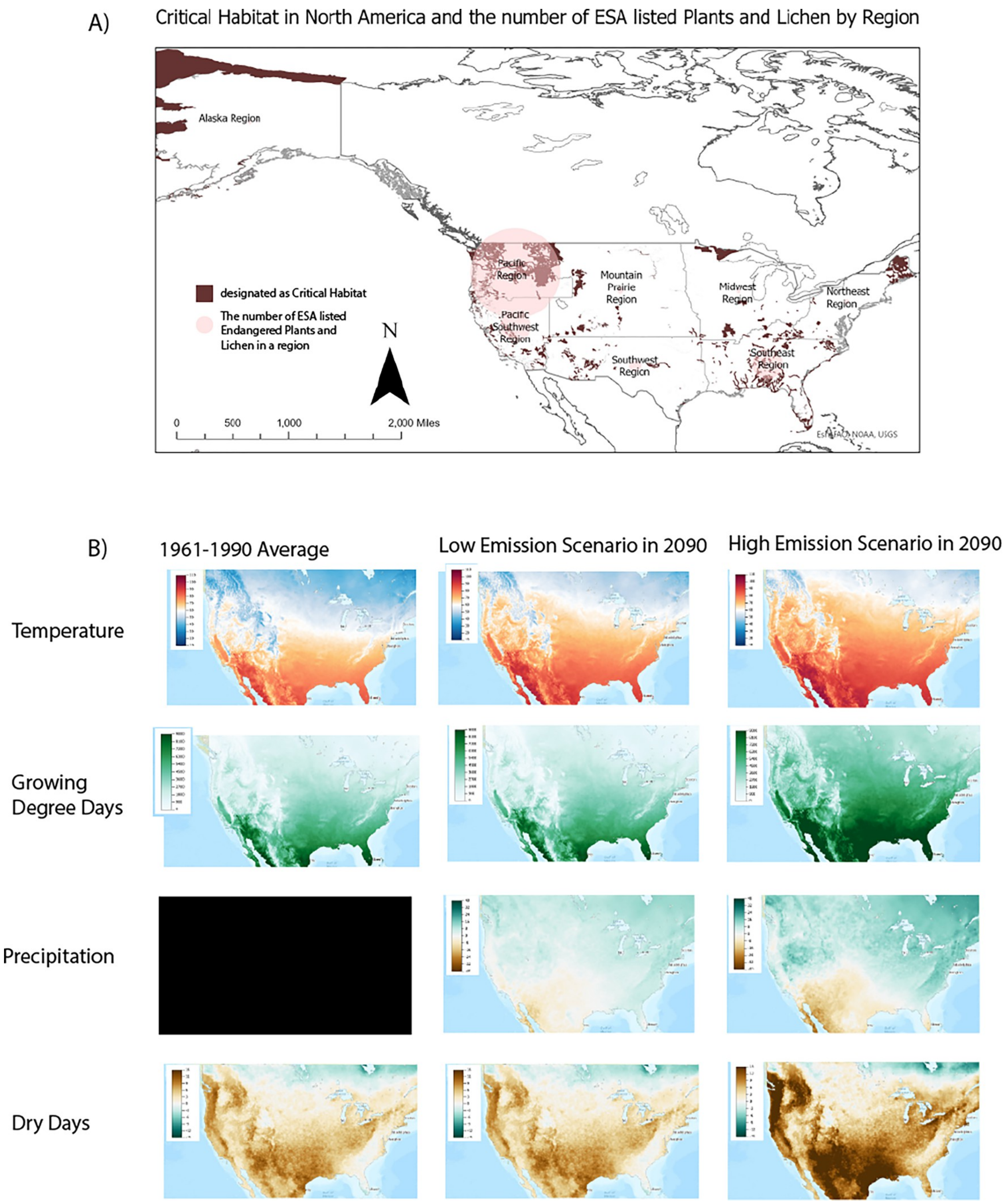

Fig 1. Critical habitat and data from the U.S. climate resilience toolkit climate explorer [22]. A. All land designated as critical habitat for both plants and animals under the Endangered Species Act is shaded in dark red. While not all endangered species are located on critical habitat, it does provide a rough distribution of endangered species. The light red circles indicate the relative number of plants in each US FWS region, with larger circles indicating a greater number of listed plants. The black outlines are US FWS regions, which are regulatory regions applied to enforcing the ESA. Region 1: Pacific, the largest circle of the map, also includes Hawai'i as well as other Pacific Islands, where most of the listed plants in this region are located. Layers used to create this map are the USFWS Region Layer (https://gis-fws.opendata.arcgis.com/datasets/c9d8cd103c5c444f9f65a1bc0dfe1b95_0/about), the USFWS Critical Habitat Layer (https://ecos.fws.gov/ecp/report/critical-habitat), and the Base Layer "Outline Map" (https://www.arcgis.com/home/item.html?id=7da16f48c81f448fa972d4a52fdc1e4e). B. "Temperature" is the average daily maximum temperature. Under high emissions, the average daily maximum temperature will increase for most locations in the continental US. "Growing Degree Days" is an estimate of the growth and development of plants. A higher number of growing degree days indicates longer durations of warm conditions. Much like temperature, the number of growing degree days is projected to increase in all areas other than the highest elevations. "Precipitation" is the total precipitation in a year in inches. Total precipitation appears to increase in the North and East

but declines in the Southwest. There was no historic data for total precipitation. "Dry days" is the number of days in a year when precipitation is less than .01 inches. Changes in this number indicate trends towards drier or wetter conditions. The dry days data indicates that in regions like the Northwest, while total precipitation may not change or may increase, there will be an increase in dry days throughout the year. Under climate change, there is the potential for not only shifts in the amount of precipitation, but also shifts in the amount of precipitation received at any given time or the form of the precipitation (i.e. snowfall, ice, or liquid rain). The Northeast, Midwest, and Southeast are particularly likely to be affected by these extreme rainfall events. These heavy rainfall events lead to an increased risk of flooding [23, 24].

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Species are also expected to shift their distributions in response to rising temperatures, with about half moving 50–1600 km towards higher latitudes or up to 400 meters higher in elevation [25]. Species are not only shifting geographically, but also in their timing, or phenology. Many species are already shifting to earlier spring breeding, migration, or in the case of many plants, blooming [25]. These changes in timing and geography may lead to cascading impacts across entire ecosystems, disrupting ecosystem functions and relationships between species.

This may impact keystone species, or species whose presence is crucial to maintaining an ecological community [26, 27] or multi-species interactions such as food webs, pollination and seed dispersal interactions [28, 29]. These shifts in phenology can have greater impacts on the larger ecosystem, disrupting trophic interactions and leading to trophic mismatches and community instability [14, 30–32]. Mismatches between the life cycles of plants and their pollinators have been of particular concern due to changes in emergence and flowering time [33, 34]. In the case of plants, the extirpation of a keystone plant could lead to cascading effects on dependent animals, particularly pollinators and seed dispersers [27]. While this study examines climate change on a species-by-species basis, climate change will impact not only an individual species, but their network of relationships in ways that can be unpredictable and lead to cascading effects in the entirety of the ecosystem.

ESA protections and climate change

In the United States, the Endangered Species Act is the primary law that protects rare species at risk of, or threatened by, extinction. The ESA initially only protected wildlife, with the first plants added in 1977 [25]. In 1982, an amendment was added to prohibit the removal of endangered plants from federal land [35]. With this addition, the number of plant species with ESA listings grew, and, since 1994, plants have made up a majority of the species listed [25].

However, despite their listing, critics of the ESA note that recovery efforts tend to focus on charismatic wildlife, leaving plants with fewer resources than other species [25, 36]. Additionally, a core feature of the ESA is the prohibition against "taking" an endangered animal. In this case "taking" would mean to harass or harm the species in addition to selling the species or their parts. This prohibition does not apply to plants. Under the ESA, plants are protected from removal on federal land or destruction in knowing violation of state law. However, on private property, there is no prohibition against "taking" endangered plants and lichen [25, 35]. So, while the ESA is often held up as a powerful conservation tool, it is less protective for plants and lichen than it is for animal species.

Rare species are assessed for listing on the ESA as either "threatened" or "endangered" by the secretaries of the Interior and Commerce- using five factors:

1. Habitat destruction and degradation
2. Overutilization
3. Disease or predation
4. Inadequacy of existing protections

5. Other factors

If this assessment find that listing is warranted, and is not precluded by other higher priorities, a species may be listed as either "threatened" or "endangered" at which point the agencies that oversee the implementation of the Endangered Species Act- in the case of plants the US FWS prepare plans and implementation for the species recovery. The primary document created in this process is the recovery plan. While agencies are not required under the ESA to implement all actions outlined in the recovery plan, the goal of recovery plans is to provide "a feasible and effective pathway to recovery" of a species [37]. From there, the ESA mandates that species periodically are reviewed. These reviews are conducted through a systematic procedure, the 5-year review. If a species has an up-to-date recovery plan, then a 5-year review will evaluate if that plan is being followed and how the species status may have changed since the previous 5-year review. If a species does not yet have a recovery plan, or the recovery plan is out of date, then a 5-year review may become a more intensive analysis of the recovery of the species. In general- a 5-year review will have the most up-to-date information on an ESA listed species [38].

Despite the growing threat of climate change for rare species, climate change is not included as one of the five evaluation factors when listing a species and creating a recovery plan. This is partially due to the timeline of legislation surrounding the ESA. The last major amendment to the ESA was in 1988 [39]. The first ESA listed animal to evaluate climate change as a primary threat for their listing was the polar bear (*Ursus maritimus*) in 2008, followed by many more species that same year [40]. Since this 2008 listing, there has not been an amendment to the ESA, so climate change continues to be generally considered either as a contributor to "Habitat destruction" or as one of the "Other factors" in a species assessment.

The US Fish and Wildlife Service (US FWS), the primary agency that oversees the implementation of the ESA for listed plants, has acknowledged climate change as a challenge to conserving wildlife and has stated that they develop conservation programs with climate change in mind [41–44]. In some cases, climate change may fall neatly under "Habitat destruction" such as rising sea levels encroaching on a narrow strip of beach habitat. However, this is not always the case. Climate change will impact species in a variety of ways that are not tied directly to habitat, such as: an increase in fungal diseases and other pathogens, phenological mismatches, a loss of obligate species, changes in disturbance regimes, and the loss of crucial climate envelopes [25, 44]. This means that while climate change may be integrated into other factors and objectives, it is not required to be considered in a holistic way while assessing species for listing and recovery under the ESA. While the immediate problem might be addressed, if the underlying cause is linked to climate change, the species may need a different approach to promote its recovery.

The threat assessment of climate change towards ESA listed organisms has been carried out previously a handful of times. In 2010, Povilitis et al. evaluated all species with recovery plans, both plants and animals. This initial analysis showed that more recent recovery plans (starting in 2004 and ending in 2010 when the study was published) were more likely to list climate change as a threat [45]. However, at the time, only 26 recovery plans listed climate change as a threat for animals, and no plant recovery plans listed climate change as a threat [25]. In 2019, Delach et al. assessed the sensitivity of 459 endangered animals to climate change, if climate change was listed as a threat, and if any actions were implemented to mitigate climate change. They found that almost all animal species are sensitive to climate change, but only 64% listed climate change as a threat and even fewer (18%) had management actions in place [40]. This more recent evaluation has not been carried out for plants.

Finally, it is important to note that endangered species are not evenly distributed across US FWS regions. In particular, imperiled vascular plants tend to cluster in the central valley of

California (FWS Region 8: Pacific Southwest), southern Appalachia (FWS Region: 4 Southeast), and the Southeast (FWS Region: 4 Southeast), these distributions and how climatic conditions may change in the future seen in Fig 1 [46–48]. Some of these trends reflect biodiversity and endemism hot spots and correspond to the three recognized biodiversity hot spots within the United States (including islands and territories): Polynesia Micronesia (FWS Region 1: Pacific), the Caribbean (FWS Region: 4 Southeast), and the California Floristic Province (FWS Region 8: Pacific Southwest) [49]. However, using the ESA as a metric for rare plants and lichens underestimates the true total number of rare and endemic plants across the United States [50–52]. Rare plants and lichens can, and do, exist across the United States but are not listed under the ESA and outstrip the capacity of the ESA. NatureServe, which evaluates the rarity of plants, has over 2800 plants ranked as G1 (critically imperiled) or G2 (imperiled) in the United States, while there were only 771 plants and lichens listed within the ESA during this evaluation [53]. Therefore, this study should be used as a conservative examination of the impact of climate change on rare plants and lichen, but also can serve as a proxy for the impact of climate change on rare plants, since ESA listed species have been evaluated for a variety of external threats.

Study objectives

The first objective of this study is to determine, based on publicly available information, how many ESA listed species are sensitive to climate change, and the intensity of that sensitivity. The second objective is to determine which factors (temperature, hydrology, disturbance, isolation, injurious species, chemistry, phenology, obligate relationships, and humidity) are most prevalent amongst the species sensitive to climate change. Finally, this study evaluates if climate change is recognized as a threat in these documents in the development of ESA listings or recovery actions. Together, these three objectives can aid in conservation planning for endangered plants and lichens, as well as inform future listing and recovery recommendations.

Methods

This study evaluates all plant and lichen species listed as endangered under the ESA in US states, territories, and surrounding waters as of June 1, 2021 (n = 771; see http://www.fws.gov/endangered). Government agencies, such as the US FWS, require the use of publicly available information [54]. As such, we carried out assessments using public and freely accessible information published by agencies and conservation organizations, primarily the FWS Environmental Conservation Online System (https://ecos.fws.gov/ecp) and the NatureServe Explorer (http://explorer.natureserve.org). The documents analyzed include ESA documents such as listing decisions, recovery plans or outlines, critical habitat designations, and five-year reviews, with priority given to the most recently published documents.

Using Delach et al. 2019 as a reference, we modified a trait-based assessment to determine how sensitive a plant or lichen species is to climate change [40]. Sensitivity is defined as the “innate characteristics of a species or system and considers tolerance to changes in such things as temperature, precipitation, fire regimes, and other key processes” [55]. The nine sensitivity factors used in our assessment, taking the form of yes-or-no questions, were drawn from already existing protocols and assessments, such as the NatureServe Climate Change Vulnerability Index and the US Forest Service’s System for Assessing Vulnerability of Species, the latter of which is a tool for assessing vertebrate species [56–58]. The nine sensitivity factors used in this assessment are outlined in Table 1. After sensitivity factors were scored, key quotes were pulled from relevant documents to demonstrate the context of the sensitivity. This allowed for

Table 1. Species sensitivity factors to climate change.

Temperature	Does the species have specialized thermal tolerance or depend on habitat with an important temperature threshold? Species were evaluated as temperature sensitive if available information indicated the species has or depends on habitats with obligate or preferential temperature thresholds (for example, river ice flows creating habitat for a species along a stream bank).
Hydrology	Is the species dependent on a habitat with a specialized hydrology? Species were evaluated as sensitive if available information indicated they require narrow ranges of water depths, flow rates, timing, or seasonality (for example, vernal pools, intermittent streams, high elevation wetlands).
Disturbance	Is the species or its habitat sensitive to or dependent on a specific disturbance regime? This includes species in fire-adapted systems, species that rely on certain flood regimes, and species impaired by disturbance.
Isolation	Is the species geographically restricted or does it face intrinsic or extrinsic barriers to shifting its range to maintain its climate space? While many endangered species are found in small, isolated populations, we scored species in this category if available information indicated they are confined to mountains, small islands or headwaters; are narrowly endemic to spatially discrete habitats, such as caves, springs, rare soil types, and micro-climates
Injurious species	Is the species or its habitat threatened by an invasive species, pest and/or disease organism that might benefit from climate change? We did not evaluate the species in question as sensitive where the injurious species are ubiquitous or human oriented. Examples of injurious species include invasive insects or introduced browsing animals such as goats or cattle
Chemistry	Is the species sensitive to changes in chemical concentration, such as atmospheric CO_2, water pH, or dissolved oxygen? In plants, these factors often combine with shifts in hydrology or soil chemistry.
Phenology	Does the species rely on specific triggers for life-cycle events, such as germination, pollination, flowering, or reproduction that are likely to become out of sync with seasonal changes in resource availability or environmental conditions (that is, phenological mismatch)?
Obligate relationships	Is the species dependent on one or a few species, such as a host plant, pollinator, or seed disperser, with limited alternatives if the required species declines due to climate change? We did not evaluate the species as sensitive if it requires a host but can succeed in association with four or more species.
Humidity	Is the species reliant on specific moisture conditions, outside of soil moisture, for survival, or live in a habitat that is defined by these conditions? This includes habitats such as cloud forests, coastal fog, or dry climates defined by a lack of humidity.

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more detailed qualitative coding to better understand what may be driving plant and lichen species sensitivity to specific factors [59].

This table defines the factors used to assess a species' sensitivity to climate change in this study, modified from Fig 1 of Delach et al. 2019 to include "humidity" [40]. Additionally, definitions of each factor have been updated with examples and information relevant to rare plant and lichen species.

During analysis, a species was evaluated as "not sensitive" by default, and only evidence-based statements would shift a species into the "sensitive" category. Therefore, some poorly studied species may be far more sensitive to climate change than the data reflects, since their sensitivities and life histories are not fully documented in publicly available sources [40]. An organism deemed not sensitive to climate change on this scale would be "not sensitive" to all nine factors, and would have a total score of 0. A highly sensitive species may be sensitive to all nine factors and have a score of 9. Many species fall between these two extremes. However, even species with one or a few sensitivities could render a species highly vulnerable to climate change, if an exposure to that sensitivity occurs over a large swath of the total population.

While the sensitivity tool created by Delach et al. 2019 is thorough, many of the key primary sources it pulls from are either wildlife-focused or exclusively examine vertebrate animals [40].

Similarly, The US Forest Service's System for Assessing Vulnerability of Species (SAVS) is another useful tool using 22 criteria to predict the vulnerability of a species to climate change, however it was originally tested and is most suited for the scoring of terrestrial vertebrate species [58]. These tools are well conceived but require alterations to truly address and assess the sensitivity of plants and lichens to climate change.

The primary factor that this study adds to the climate change sensitivity scale is humidity. While temperature and hydrology, in many cases, are well understood in the context of climate change, it is expected that humidity will become highly variable under future climate change scenarios [60]. In forest ecosystems in particular, relative humidity has been shown to impact stomatal conductance, transpiration, and plant tissue water [61, 62]. Additionally, specific habitat types rely on marine fog and cloud cover, rather than ground water, to fulfil their hydrological needs [63–67]. Studies have shown that habitat types reliant on humidity and marine fog will be impacted, potentially positively [68–70] or negatively [71], by climate change. For these reasons, humidity was included as a sensitivity factor in this study, so our protocol assesses nine factors.

Additionally, we examined ESA documentation (such as: species status assessments, recovery plans and amendments, five-year reviews, and designations of critical habitat) to see if climate change was recognized as a threat to a species and if any actions were being taken to mitigate the threats posed by climate change. The goal of this analysis was to examine if there were any discrepancies between the frequency that climate change was recognized as a threat in comparison to how often actions were taken to address those threats directly. Actions where on-the-ground obtainable recovery goals, such as continued monitoring, or establishing a seed bank for a species, while acknowledging that climate change is the threat driving these actions.

When evaluating a species for if climate change was recognized as a threat: a species would only be moved into the "recognized as a threat" category if climate change was explicitly named. In some documents, climate change is alluded to without being explicitly named. Under the coding scheme, a species like this would be given a "not recognized as a threat" score. Finally, if climate change was explicitly identified as not a threat, the species was labeled "not a threat." The goal of this analysis was to understand how often climate change was being recognized by ESA assessments, regardless of the resources and constraints to addressing the issues climate change may raise for endangered plants and lichen.

We then asked: are conservation actions being taken to address the threats of climate change? If actions to mitigate the threats of climate change were not mentioned, the species received a score of "No Discussion." In cases where climate change was explicitly identified as not a threat, the species received a score of "No Threat and No Action Needed." For certain species, climate change is identified as a threat and there is a recognized general need for further research. These species then received a score of "Further Study." Where climate change is acknowledged as the rational for a conservation action, the species was given the score of "Action".

During analysis of documents for "threats" and "actions," coding was done conservatively. As a result, the numbers from this study are minimums rather than maximums in terms of climate change recognition and action. Additionally, some species only had listing decisions available as documentation. Listing decisions do not contain actions, so these species were classified as "newly listed."

Finally, it should be noted that two lichens- *Cetradonia linearis* (FWS Region 4: Southeast) and *Cladonia perforata* (FWS Region 4: Southeast)—are listed amongst the plants. There is no other federal system that assesses rare and at-risk fungi [72]. While the threats of climate change to fungi are likely varied and unique, due to the lack of organized conservation initiatives surrounding fungi, if these two lichens were not included in this review it is likely that they would be excluded from systematic evaluations of climate change impacts on rare and endangered species entirely. Additionally, this review is derived from a similar study examining the impacts of climate change in wildlife- so while the accuracy may be decreased for the two lichen species, it would likely evaluate them as under-sensitive, rather than over-sensitive, to climate change. The impact of climate change on fungi is a growing area of research and should be addressed in future ESA listings [44, 73, 74].

Results and discussion

Species sensitivity to climate change

All of the 771 evaluated endangered plant and lichen species were sensitive to at least one climate change sensitivity factor. These sensitivities were derived from publicly available data, and were assessed regardless of it the documentation discussed climate change as a threat to the species. As seen in Fig 2, regardless of region, the mean sensitivity was at least 4 factors, with some regions such as the Southwest, Mountain Prairie, Northeast, Midwest, and Southwest all having average sensitivity ratings above 4. Many regions had species that ranked as highly sensitive with some species having a score of 8/9- indicating that they are highly sensitive to climate change.

The exact distribution of sensitivities may vary from region to region (Fig 2). FWS Region 8: Pacific Southwest had a total of 134 species, a mean score of 5.15, a minimum score of 2, a maximum score of 8, and a standard deviation of 1.29. FWS Region 7: Alaska had a total of 1 species, a mean score of 4, a minimum score of 4, a maximum score of 4, and a standard deviation of 0. FWS Region 6: Mountain Prairie had a total of 17 species, a mean score of 5.24, a minimum score of 1, a maximum score of 7, and a standard deviation of 1.83. FWS Region 5: Northeast had a total of 7 species, a mean score of 5.86, a minimum score of 3, a maximum score of 8, and a standard deviation of 1.55. FWS Region 4: Southeast had a total of 134 species, a mean score of 4.43, a minimum score of 1, a maximum score of 8, and a standard deviation of 1.44. FWS Region 3: Midwest had a total of 3 species, a mean score of 5.33, a minimum score of 5, a maximum score of 6, and a standard deviation of .47. FWS Region 2: Southwest had a total of 41 species, a mean score of 6.07, a minimum score of 2, a maximum score of 8, and a standard deviation of 1.58. FWS Region 1: Pacific had a total of 434 species, a mean score of 4.07, a minimum score of 1, a maximum score of 8, and a standard deviation of 1.16.

Species sensitivity to climate change is not restricted to a single region of the United States and territories. Plants will be faced with changing conditions and exacerbated sensitivities, regardless of region.

It is important to note what is and is not being measured by the data. Sensitivity in this case stems from the IPCC fourth assessment and is intended to be taken into account with both exposure and adaptive capacity to examine the overall measure of concern, or vulnerability, of a species to climate change. [75]. Sensitivity and adaptive capacity are two intrinsic factors to climate change risk evaluation and are often difficult to differentiate. Sensitivity is the degree to which a system, or in this case species, is affected by climate change, while adaptive capacity is the ability of a species to adjust to climate change and moderate negative impacts [12, 75, 76]. Tools for evaluating the adaptive capacity in the face of climate change have been developed, such as those by Thurman et al. 2020. The evaluation conducted here focuses on the intrinsic sensitivities of species, and how they will be affected by climate change [12].

With these definitions in mind, this means that all regions have a large proportion of plants that are highly sensitive to climate change. All ESA listed plants and lichens are at least somewhat sensitive to climate change as all plants and lichens have a score of 1 or greater. These results, however, do not evaluate these species' ability to adapt to climatic changes and

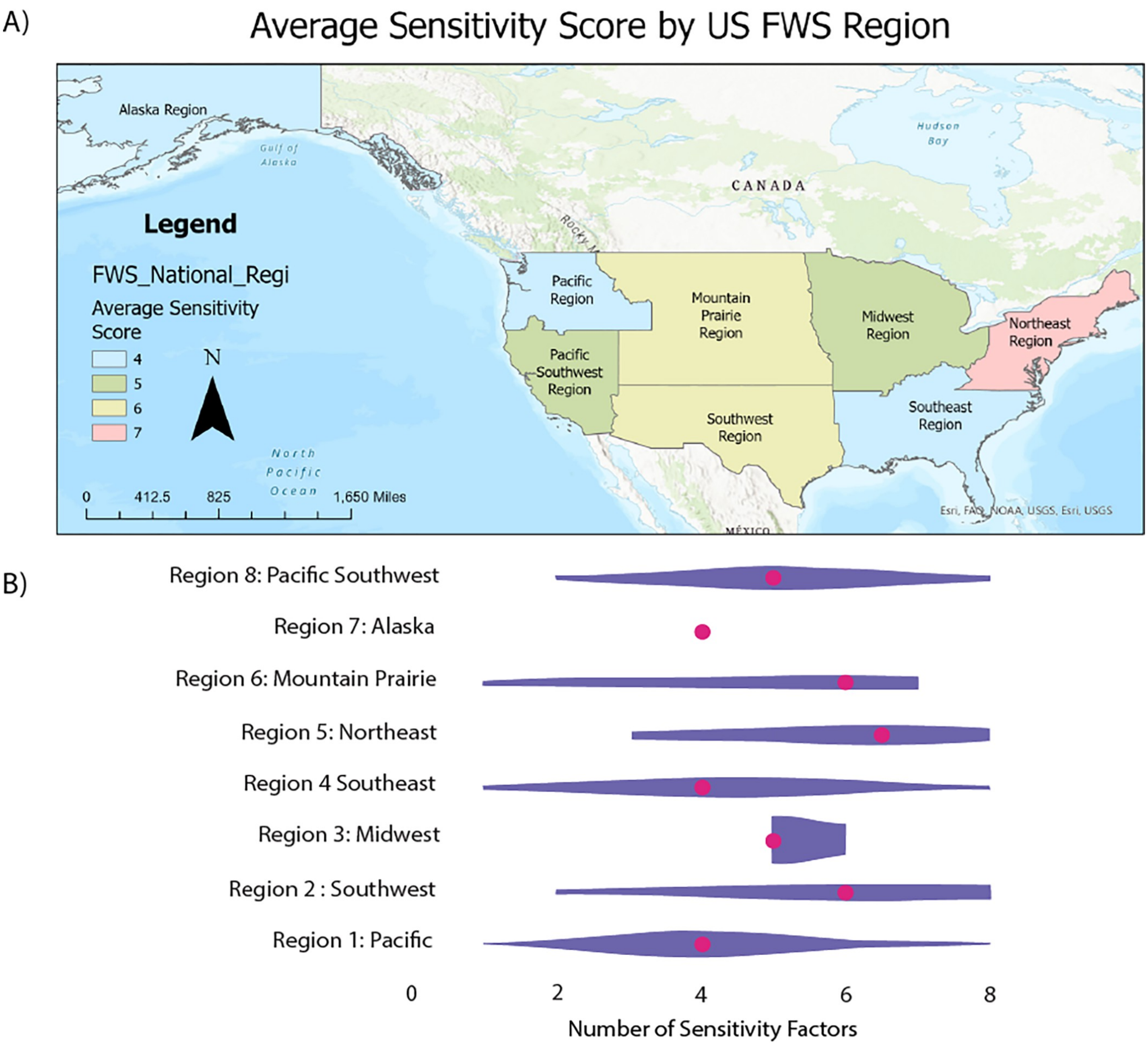

Fig 2. Species sensitivity to climate change. Layers for the map include the USFWS Region Layer (https://gis-fws.opendata.arcgis.com/datasets/c9d8cd103c5c444f9f65a1bc0dfe1b95_0/about), the Base Layer World Topographic Map (https://www.arcgis.com/home/item.html?id=7dc6cea0b1764a1f9af2e679f642f0f5), and the Base Layer World Hillshade (https://www.arcgis.com/home/item.html?id=1b243539f4514b6ba35e7d995890db1d). A) A color-coded map indicating the average sensitivity score for each US FWS region. B) A violin plot of the sensitivity factors within each region, all regions had a mean sensitivity of 4 or higher.

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pressures. It should be noted however, that rare plants are often regionally restricted and genetically bottlenecked, both limiting factors for a species ability to adapt to new conditions [12]. Therefore, climate change sensitivity should be evaluated, regardless of geographic location, and all ESA listed plant and lichen species are at least slightly sensitive (score of 1 or greater) to climate change.

Prevalent sensitivity factors

Disturbance and injurious species were some of the most prevalent climate change sensitivities in listed ESA plants and lichens (Fig 3). This is not true of all listed endangered species, as disturbance was the least common sensitivity across endangered animals, suggesting that disturbance is of particular concern for plants [40]. Factors such as disturbance, disease, and herbivory (the last two being components of "injurious species") may be of particular concern for plants as individuals cannot move. This lack of mobility is only heightened by the fact that many ESA listed plants and lichens live in highly specific habitats [77]. Of the 771 evaluated plants, 38.66% (n = 283) were sensitive to all movement-oriented factors (disturbance, isolation, and injurious species.) Approximately the same percentage of species were sensitive to at least two of these factors (Isolation and Disturbance at 39.81% n = 307 and Isolation and Injurious Species at 43.44% with n = 318). A vast majority of evaluated plants, at 86.25% (n = 665) were sensitive to both injurious species and disturbance. Meaning, if a perturbance, such as an extreme weather event or a pest or fungal invasion, impacted the entirety of a habitat that a species is found in, the species could be wiped out in a single event. Even if a species in this scenario could disperse their seeds, they would likely only be able to find suitable habitat in the now-perturbed region. Scenarios such as these are likely to become more frequent under the effects of climate change. For example, *Allium munzii*, or Munz's onion, occurs only in a microhabitat which contains high soil moisture within the Perris Basin [78]. Like many endangered plants, if a perturbance were to occur within the moist microhabitat of the Perris Basin, this species would likely become extinct. In this case, additional studies on the adaptive capacity of endangered plants and lichens could prove useful to better understand how species may respond in-place to climate change [12, 79].

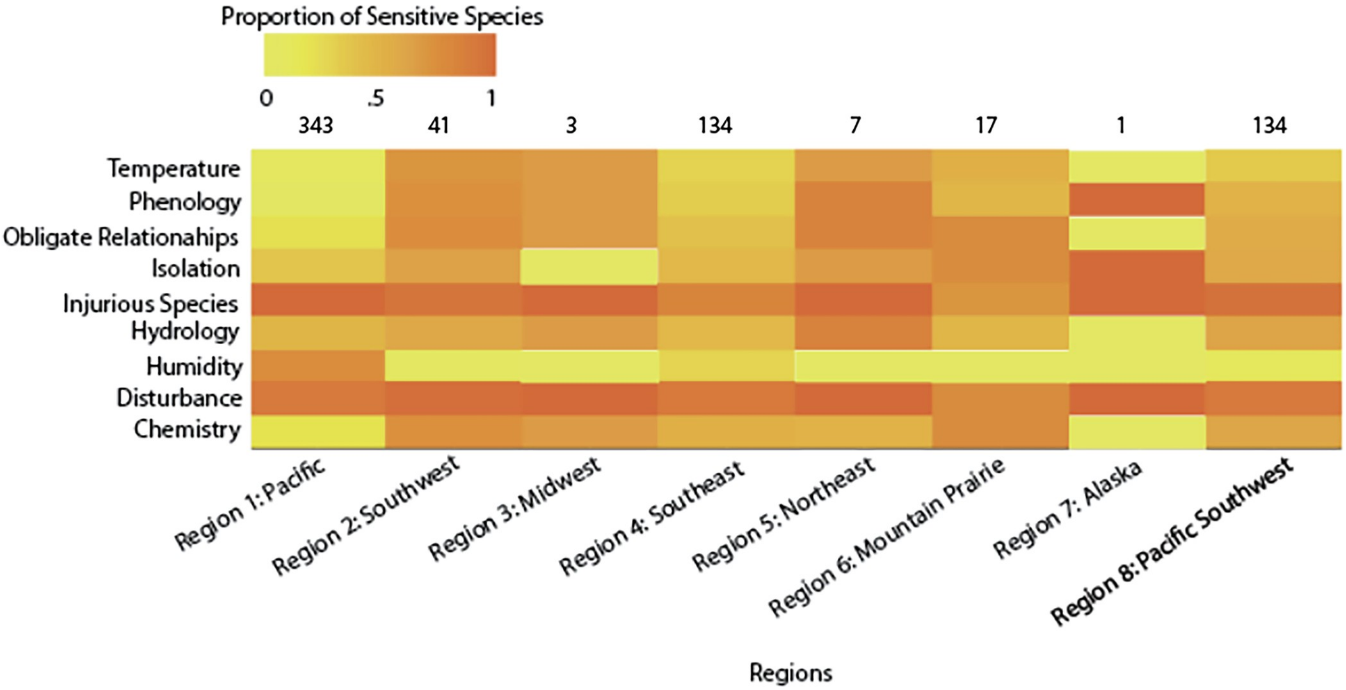

Fig 3. The Nine Sensitivity factors and their prevalence in each US FWS region. The nine sensitivity factors and their frequency within each region. A yellow color indicates that the factor scored a "yes" infrequently in that region, while a dark orange indicates that it is a frequent climate change sensitivity factor for that region. Overall, disturbance (n = 699) and injurious species (n = 733) were the most significant risk factors across all regions.

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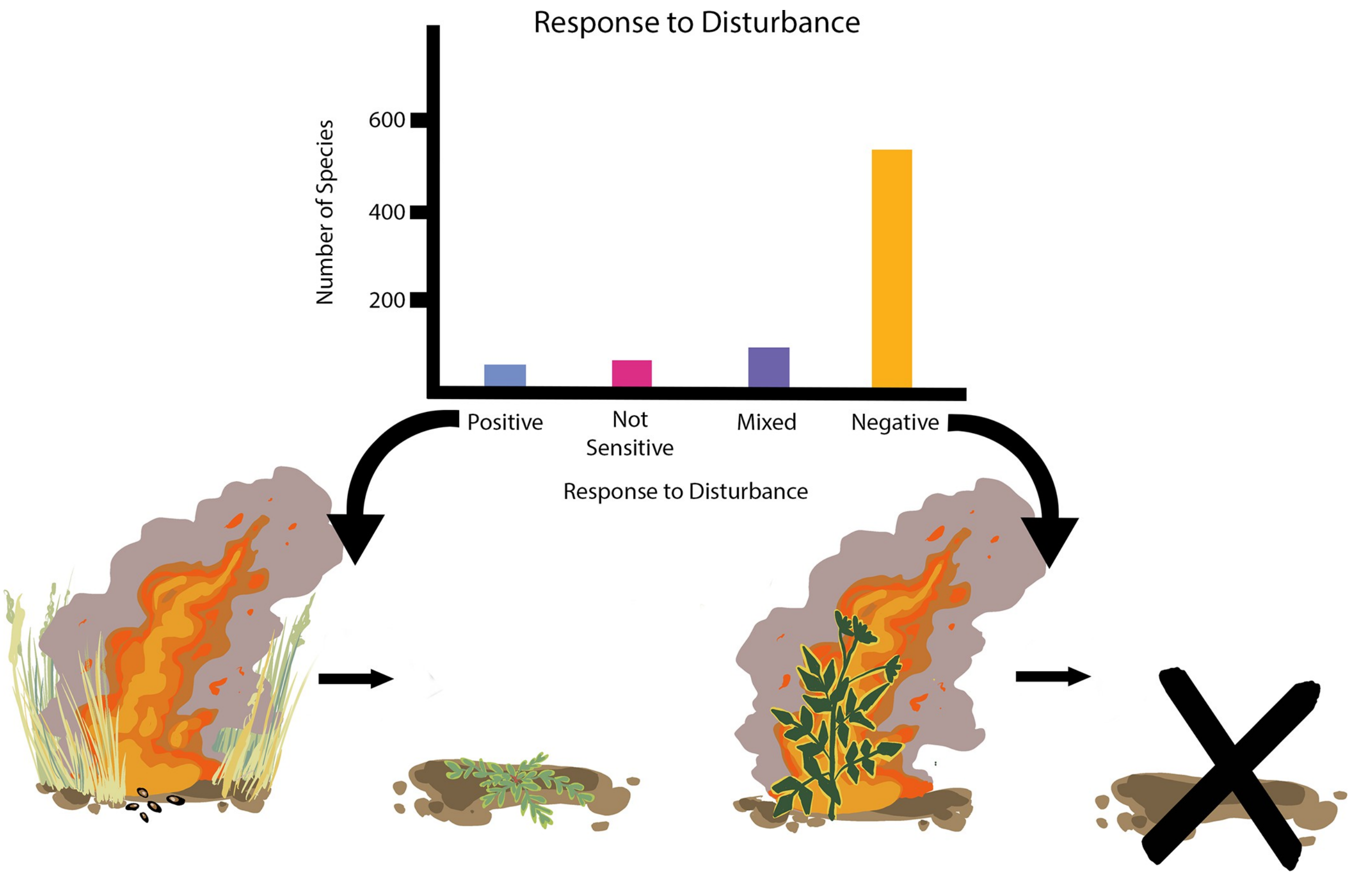

Fig 4. The response of ESA listed plants and lichens to disturbance. A majority of plants and lichens were sensitive to disturbance, but almost all had a negative response (n = 534), killing or damaging the plant or its reproductive organs. A small number had a positive response (n = 67), requiring a disturbance to thrive. A larger number had a mixed response (n = 97)- where they may tolerate or require one disturbance but are susceptible to another. Some plants were not sensitive to disturbance so were scored as “not sensitive” (n = 73).

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In addition to the scenario outlined above, disturbance can have positive as well as negative impacts and is required for many species to thrive across a variety of habitats [80, 81]. Therefore, species reliant on disturbance may also be impacted as these disturbance regimes shift due to climate change. This makes the prevalence of disturbance as a sensitivity factor all the more complex- as in this study it encapsulates both destructive and regenerative processes. A single species could rely on a specific disturbance at a specific intensity or frequency, but a change of intensity of that disturbance, or other unrelated disturbances, could negatively impact the species. Disturbance being the most common sensitivity factor for plants indicates this complex relationship needs to be taken into account when planning for climate change mediation for plant species in particular. Simplistically, sensitive species could either have a positive response to a disturbance (such as germinating after fire), negative (such as a hurricane destroying a population), or mixed (that they were benefited by some disturbance and to the harmed by others). In Fig 4 we can see that a majority of ESA listed plants have negative responses to disturbance, but some do show positive or mixed responses.

A common disturbance that can have positive impacts for specific plant communities is fire. Fire regimes in the western United States have been heavily studied, with fires becoming more frequent and intense with warmer and drier conditions [82]. For example, a cluster of endangered plants, the Gabbro Soil Plants to the east of Sacramento, California [*Calystegia* *stebbinsii* (Stebbins' morning-glory), *Ceanothus roderickii* (Pine Hill ceanothus), *Fremontodendron californicum* ssp. *decumbens* (Pine Hill flannelbush), *Galium californicum* ssp. *sierrae* (El Dorado bedstraw)] are all reliant on disturbance through fire for their life histories [83]. Though each species has a unique response to disturbance and climate change, they all inhabit a chaparral and woodland community adapted to a specific fire regime While these species currently suffer from a lack of fire, there is concern that these changing fire regimes to more intense fires may negatively impact some species. These processes can occur through the destruction of normally fire resistant tissues, seeds and other reproductive organs, or the in-soil seed bank [84–86].

It is important to note that these are factors that plants are already sensitive to- collected from currently publicly available data. It is possible that plants that currently do not have these sensitivities to climate change may develop them as the full impacts of climate change become more apparent. Milder winters, warmer growing seasons, and changes in moisture- all consequences of global climate change- have been linked to potential increases in pathogens and insects that target plants [87]. In this case, while many species are already highly sensitive to injurious species and disturbance, shifts in climatic conditions could exacerbate these threats, or introduce new threats to species that currently are not present in the region. Climate change will cause conditions to shift in ways that we have yet to predict, and stress plants in ways that we cannot see in their current contexts and environment. However, this is all the more reason that clear climate change sensitivity should be addressed proactively.

Threats and actions being taken to address climate change

In the ESA documents examined, climate change is overwhelmingly acknowledged as a threat. Eighty nine percent of endangered plant species listed climate change as a threat (Fig 5). Unfortunately, direct actions to mitigate the threats of climate change are infrequent. Only 28 out of 771 species had direct action to address climate change impacts (Fig 5). A majority (428) did not mention any climate change action for endangered plant species. These results show an even larger divergence between threat and action for plants and lichens than shown in similar studies done examining the threat and actions taken to address climate change in endangered wildlife [40]. This is a wider concern for ESA listed species, outside of plants. Acknowledging climate change as a threat is a key first step, however unless actions are directly taken, species could be at further risk.

However, not all regions address climate change with tangible actions with the same frequency. Fig 5 shows that a majority of listings with actionable items came from FWS Region 1: Pacific at 39.28% (n = 11) and FWS Region 8: Pacific Southwest at 32.14% (n = 9). However, these two regions contain the most ESA listed plants overall. Of the total number of species in each region that proportionally had the most action items within the region, two smaller regions show the most promise. FWS Region 2: Southwest had 9.75% of all species in the region (n = 4/41) with actionable items addressing climate change, and FWS Region 6: Mountain Prairie had 11.76% of all listed species in the region (n = 2/17) having actionable items attributed to climate change. Despite these promising numbers, some regions (FWS Region 2: Midwest (n = 3), FWS Region 5: Northeast (n = 7), FWS Region 7: Alaska (n = 1)) do not have any listed plants with action plans that incorporate climate change. These regions also have the fewest listed plants- which could be an indication that a lack of resources in this region may be contributing to a lack of conservation action. However, of the 28 species there are several key-ways that recovery actions can take climate change into account. In Table 2 quotes were pulled from select species that all included climate change actions in their recovery planning documents. Since the 5-year review process is meant to be comparable across regions, these

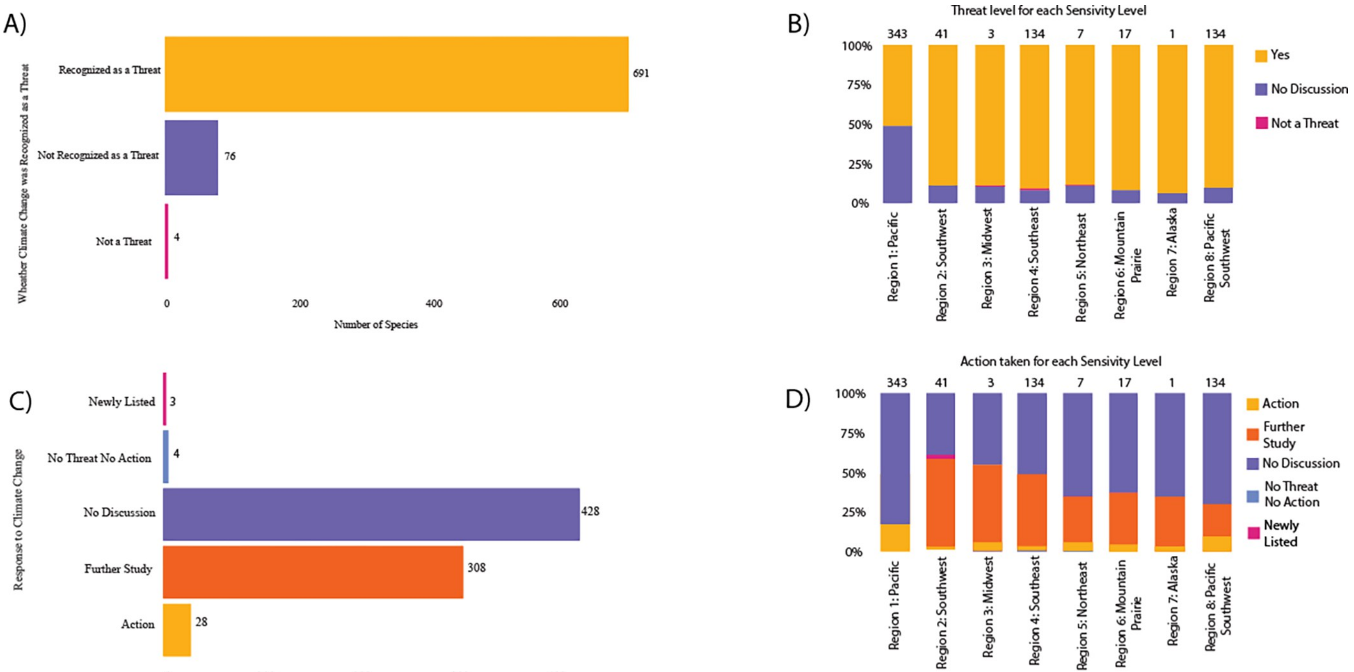

Fig 5. Is climate change recognized as a threat to endangered plants and lichen, and what actions are being taken?. A) Depicts results of number of species where climate change was recognized as a threat, not recognized as a threat or there was no threat. Overwhelmingly, climate change is listed as a threat to endangered plants with 89% (691/771) threatened by climate change. B) The frequency that climate change was listed as a threat by region. Most regions discuss climate change as a threat more than half the time. Climate change was identified most frequently as a threat in FWS Region 1: Pacific, with 99.07% of plants listing climate change as a threat, and least frequently in FWS Region 7: Alaska, which only has one endangered plant species. C) Represents if actions against the threat of climate change are being taken to mitigate the impacts. Only 3% (28/771) of endangered plants had direct actions being taken to mitigate the impacts of climate change. A majority of plants have no direct actions taken with either Further Study or No Discussion, together at 95.5% (736/771). D) The frequency of climate change is addressed by region. Only in FWS Region 1: Pacific did a category other than "No Discussion" make up the majority. In FWS Region 1: Pacific, "Further Study" was the most common category at 64.05%. The most common region to have action being taken to address climate change was FWS Region 6: Mountain Prairie at 11.76%.

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Table 2. Actions taken to mitigate climate change.

Summary of Action	Species and Region	Key Quote
Linking climate change to other risks	*Caulanthus californicus* FWS Region 8: Pacific Southwest	"Analyze the potential for habitat degradation due to climate change and nitrogen deposition, as well as threats to pollinators from regional pesticide use. Appropriate measures to ameliorate these threats should be implemented"– 5 year review 2020
Maximizing the future adaptive capacity of a species	*Diplacus vandenbergensis* FWS Region 8: Pacific Southwest	"Expanding the boundary to 1mi. . . .created larger and contiguous blocks of suitable habitat, which have the highest likelihood of persisting through the environmental extremes that characterize California's climate, and of retaining the genetic variability to withstand future stressors (such as invasive, nonnative species or climate change)." -Critical Habitat 2015
Targeted monitoring	*Lilaeopsis schaffneriana var. recurva* FWS Region 2: Southwest	"Much of the range of L. schaffneriana spp. recurva is impacted by climate change and drought, as well as groundwater pumping. This taxon is particularly vulnerable to even small losses in groundwater availability. Therefore, it is important to monitor water availability through time, in addition to monitoring the response of L. schaffneriana ssp. recurva." Recovery Plan 2017
Exacerbation of current risks	*Pediocactus despainii* FWS Region 6: Mountain Prairie	"Programs to control excessive herbivory or predation will be developed to adaptively manage each population. . . .and must take into consideration the degree which climate change may impact disease and herbivory levels in the future"– 5 year review 2019
Creation of climate refugia and seed banking	*Pediocactus knowltonii* FWS Region 2: Southwest	"A minimum of one new climate refugia population will be established outside the current range of the species and be maintained occupied at least 75 percent of a 20-year survey period (15 years). Alternatively, a robust seed banking program could be established, thus providing the potential for species resiliency over evolutionary time" -Recovery Plan amendment 2019

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documents can serve as a point of reference for future USFWS 5-year reviews and recovery plans [78].

As demonstrated in Table 2-regions took a variety of approaches to addressing climate change, many amending actions that were already being taken- such as continued monitoring of environmental conditions with climate change in mind, or conserving reproductive material and genetic resources. Other actions were unique and new additions for climate change threats, such as out-planting initiatives for species that may be facing imminent habitat destruction into potential climate refugia. As seen by the examples in Table 2, climate change conservation actions can utilize a variety of strategies, depending on the budget allocated for the species and its specific sensitivities and needs. There is no one-size-fits-all strategy for the mitigation of climate change, however there are many smaller steps that conservation plans can integrate into existing recovery strategies.

Considering the lack of actions being taken: should climate change be a factor added to ESA listings? The current regulatory status of Climate Change, where it may be listed either under "Habitat Destruction" or "Other Threat", and it currently requires outside evaluation to understand how well climate change is being factored into conservation plans for endangered species. Adding climate change as a required evaluation factor would ensure that climate change was being evaluated in all species listings and prevent the delisting of a species if a climate change impact does not neatly fall into a preexisting category. Considering how few species currently have actions directly addressing climate change, adding climate change as an evaluation factor could create clearer conservation guidelines and targeted recovery objectives.

Ideally, regulatory change would allow the ESA to adapt and incorporate climate change more fully into the scope of the law, as has been done with amendments to the ESA in the past [35, 39]. These changes could potentially allow for climate change to be considered in the recovery of a species and enforced in a systematic way. However, due to political conditions surrounding climate change in the United States, any change to the ESA is unlikely to occur [88]. The reality of the situation is that reviews such as this one are critical for assessing the overall trends in recovery plan and 5-year review documentation, and make clear where assessments could be improved in the future. Individual administrations may choose to restrict how climate change is evaluated in assessments, as seen with the Trump administration, or broaden evaluation criteria surrounding climate change, as seen under the Biden administration [89, 90].

Conclusion

Conservation actions through the ESA make a tangible impact for endangered plants, and could be used as a tool to mitigate the impacts of climate change. Since climate change is not required to be a factor or written into the ESA, it is left to US FWS Service staff on whether climate change is even recognized in threat assessment for possibly vulnerable plant species. For species that are at risk, a political shift, even for just a few years, could mean major long term set-backs for a species long term. However, the US FWS must follow the directions given to their agencies.

Additional studies must be conducted to show the direct impact of climate change on endangered plant species. Drawing direct and scientifically rigorous connections between climate change sensitivities and listed species will allow ESA enforcing agencies to be able to make stronger cases for including climate change as a direct threat to endangered plant species. Making a strong connection between individual species and the threat of climate change could improve recommendations for direct conservation actions to mitigate these risks.

For species to continue to recover and thrive as the climate changes, more recovery plans will need to directly integrate climate change related actions. While directly considering climate change is not currently required by the ESA, listing climate change mitigation as a clear goal of a conservation plan will help to direct future conservation actions as well as funds. Some species may already be having their climate change sensitivity needs met through existing recovery plans without directly addressing climate change, however as conditions continue to shift over the next century, clear and focused objectives will likely become even more vital for successful species recovery.

Supporting information

S1 Data. A database of all endangered plants with key quotes extracted from ESA documentation as well as their sources.
(XLSX)

S2 Data. Key pieces of data reformatted for quantitative data analysis on the sensitivity factors of each ESA listed species.
(XLSX)

S3 Data. Key pieces of data reformatted for quantitative data analysis on the climate change threat and actions taken for each ESA listed species.
(XLSX)

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