What we need to know to prevent a mass extinction of plant species

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Social Impact Statement
Human actions are driving plant species to extinction at rates a hundred to a thousand times faster than normal. To prevent extinctions, it would be helpful to have a more comprehensive taxonomic catalogue and much greater knowledge of where plant species live. Addressing these questions must be a scientific priority. However, what we know at present is enough to effect practical conservation actions, such as protecting more land in biodiverse places, reconnecting fragmented habitats, and eliminating species introduced outside their native ranges. For the benefit of people and the planet, we can, and must act on what we know already, to prevent catastrophic plant extinctions.

Summary
Continuing destruction of habitats—and especially tropical forests—the introduction of plant and herbivorous animal species outside their native ranges, and global climate disruption all contribute to the extinction of plant species. What can we do to prevent this? Do we have enough basic information to make effective conservation decisions? First, how many plant species are there? This question has an easy element—how many species we know now—and a much more difficult one—how many do we not know. Second, where are the concentrations of plant species? Third, where are the species we do not yet know? Fourth, what plant species have gone extinct, and where did they live? A related question is which species are threatened with extinction and where do they live? Fifth, how well can we map threats to species? For habitat loss, remote sensing provides satellite images globally and very frequently. It does so at a resolution that often displays individual trees and bushes. Sixth, supposing we had detailed answers to the previous questions, what are we doing to protect species? How well does the existing network of protected areas encompass species, especially those with the smallest ranges? Does that network allow for species moving upslope as the climate heats up? How well are managers doing in removing introduced species? Although answering these questions must be a scientific priority, we cannot wait until we have all the answers. We can, and indeed must, act on what we know already.

Keywords
biodiversity, climate disruption, extinction, hotspots, introduced species
INTRODUCTION

The diversity of plant species is at considerable risk from human activities that include habitat destruction, the introduction of plants and herbivores outside their native ranges, and anthropogenic climate change (Pimm & Raven, 2017). The rates of plant extinctions (Humphreys et al., 2019) are hundreds to thousands of times greater than rates of diversification (De Vos et al., 2015). The critical question is, what can we do to prevent plant extinctions? This article asks whether we have enough basic information to make effective conservation decisions. The answer is that we do know a lot, but critical gaps remain. Filling those gaps must be a scientific priority, but we cannot wait until we have all the answers.

Here, I discuss what we do and do not know under the following headings:

• How many plant species are there?
• Where are they concentrated?
• Where are the species we do not yet know?
• What and where were the species that have become extinct?
• How well can threats to species be mapped?
• In the light of these questions, what are we doing to protect species?

1.1 How many species of plant are there?

The question as to how many plant species there are comprises two parts: an easy part to answer—how many species we know now; and a much more difficult one—how many do we not know? A collaboration between Kew and the Missouri Botanic Garden created the Global Plant List, www.plantlist.org. It lists 351,000 species of vascular plants, made up of 304,000 flowering plants, 1,100 species of gymnosperms, 10,600 species of ferns and lycopsods, and 35,000 species of mosses and liverworts. There are about twice as many synonyms—different names given inadvertently to the same species. Dividing these up between those considered to be valid species and those that were not, The State of the World’s Plants (Kew, 2016) estimates that, with synonyms resolved, about 391,000 named vascular plant species are considered valid. This number is essentially the same as the 400,000 estimated earlier using a similar process (Pimm & Joppa, 2015; Pimm & Raven, 2017). The World Checklist of Selected Plant Families (WCSP: http://apps.kew.org/wcsp/) is gradually analysing the numbers, family by family.

How many vascular plant species remain to be named? The rate of description of species new to science shows the taxonomic catalogue to be far from complete. As the supply of undescribed species falls, one might expect the rate of species description to decline. It has not (Joppa et al., 2010). For example, from 1950 to 2000, starting with approximately 70,000 species of monocots, the numbers of newly described species in the World Checklist increased from a few hundred every five years to over a thousand. Figure 1 shows a smaller sample of non-monocots with much the same pattern.

An underlying cause was that progressively more people have become involved in describing species: from about 50 to 250 per year worldwide for monocots (Joppa et al., 2010). Correcting for the increased numbers of people scientifically describing new species, the adjusted rates of species description decline (Figure 1) allow statistical models to predict when no more unknown species will remain. These models suggest that there will be another 15% more flowering plant species—a number that matches expert opinions, solicited plant family by family. If there are another 60,000 or so plant species to be named, then perhaps half of them are already present as specimens in herbaria (Bebber et al., 2010). Many of these are in groups that taxonomists are not studying actively.

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1.2 | Where are the concentrations of plant species?

Brummitt et al. (2020) has considered this question, so I will not elaborate. The challenges are considerable, however. Suppose we require our analyses to be of species that have undergone a recent taxonomic assessment to eliminate species names that are likely synonyms for other species. Moreover, we require provenance. By this I mean that a species must be placed with certainty into a location, rather than there being estimates of how many species occur across a landscape.

Joppa et al. (2013) analysed a subset of ~109,000 species from The Plant List, taken from the World Checklist of Selected Plant Families. For this subset, taxonomists have resolved the vexing issues of synonymy in determining which species are currently accepted as valid. Flowering plant species in the WCSP are tagged to one or more of the 368 countries or geographic regions within large countries delineated by the International Taxonomic Database Working Group’s geographic scheme (Brummitt et al., 2008). Figure 2 shows familiar patterns: high concentrations of species in the tropics, and high concentrations of endemics—those found in

**FIGURE 2** Numbers of species in the 368 countries or geographic regions within the International Taxonomic Database Working Group’s geographic scheme. (a) All species; (b) those endemic to the region. The data are based on ~109,000 plant species and scaled to 100,000 plant species and to 1,000 km². From data in (Joppa et al., 2013)
only one region—that differ in their details. In the absence of range maps for all the species, the very different sizes of the 368 regions cause problems. Based on species per unit area, small areas show as being more important than large ones because species numbers increase more slowly than does area. Thus, Norfolk Island has 41 endemics within this subset of ~109,000 species in an area of 63 km². Cuba has 1,203 species in an area of 110,000 km². That said, the results quantify and broadly support the patterns of endemism shown by Myers et al. (2000) and closely match much more fine-grained patterns for vertebrates (Jenkins et al., 2013). They confirm that species are very concentrated: 67% of plant species live within 17% of Earth’s ice-free land surface.

The data also inform what fraction of species lives on islands. For islands up to the size of the South Island of New Zealand (153,000 km²) the answer is 8%. This size is entirely arbitrary, but introduced animals and plants are a major threat to New Zealand’s native flora and fauna and smaller island biotas elsewhere. Certainly, introduced plant and animal species do not threaten all island endemics, and they do threaten species living on continents. That said, the percentage provides some rough estimate of the fraction of plants that invasive species may threaten.

Second, where are the concentrations of plant species? To set priorities, the simple-minded solution would be to target such places for conservation, with particular focus on the tropics, especially tropical moist forests. This approach is inadequate in two ways. As Myers (Myers, 1988: Myers et al., 2000) was the first to point out, not all such forests are of equal concern. It has long fascinated biogeographers (Willis & Yule, 1922) that the sizes of geographical ranges of plants and animals are massively skewed. As diverse examples in Pimm et al. (2014) show, there are many species with small ranges. Enquist et al. (2019), examining records of plant species, find that over a third are known from five or fewer observations. Simply put, a lot of species are rare. Interestingly, such rare species concentrate in places that are often not where the greatest numbers of all species live. These concentrations are mostly in tropical forests, but not always: the list includes many islands and other habitats including dry forests and Mediterranean ecosystems.

The second inadequacy is that these special places extend for hundreds of thousands of square kilometres. Brazil’s coastal moist forests, for instance, cover roughly a million square kilometres. Practical conservation actions, such as establishing protected areas, are likely to cover ten square kilometres or less. We need knowledge of species distributions at these smaller scales.

1.3 Where are the species we do not yet know?

It is reasonable to hypothesize that we are likely to find unknown species where there are concentrations of species, and where there are most species with small ranges. How might the predicted 15% of plant species taxonomists have still to describe affect the patterns shown in figure 27? Joppa et al. (2011) applied their model based on species described per taxonomist to different regions. Figure 1 shows the example of Colombia, Ecuador, and Peru, a biodiversity hotspot already known to be rich in endemic species. It is typical of the other hotspots in that the numbers of species described annually are increasing rapidly. Importantly, there is no decline in the numbers of descriptions per taxonomist. That ratio has remained more or less constant for about a century. This fact means that the statistical model makes only very uncertain predictions of exactly how many more species botanists will find. It only anticipates that there will be many more. The models predict that quite generally, the global set of hotspots are where most as-yet-unknown species live.

1.4 Where are the species that have gone extinct or at risk of doing so?

What plant species have gone extinct and where did they live? The related question is which species are threatened with extinction, and where do they live? One expects the answers to both questions to be similar, of course (see, for example, Vorontsova et al., 2020). Notice that the distribution of known plant extinctions (Humphreys et al., 2019) closely matches the concentrations of endemic species shown in Figure 2. The similarity of plant to animal extinctions extends to the rates at which they go extinct, too. Vorontsova et al. show that those rates are somewhat lower for plants, but that for both plants and vertebrates, the rates for species described in the 20th century are higher than for those described in the 19th. The explanation is that generally, taxonomists describe species with large ranges first—they are easy to find—and those with smaller ranges later. In South America, half of all the bird, mammal, and amphibian species with ranges of <20,000 km² have been found in the last 30 years (Pimm et al., 2010). It seems probable that many plant species with small ranges have gone extinct before taxonomists had a chance to describe them.

To prevent further extinctions, one needs to know which species are threatened and where they occur. The International Union for Conservation of Nature (IUCN) Red List (www.iucnredlist.org) is the international authority that deems species to be threatened. Decisions combine the vulnerability of a species with the threats facing it. In most cases, threatened species are likely to be rare in that they have small geographical ranges or low local abundances and, in practice, likely both. Certainly, there are threatened animal species that have huge geographical ranges but occur at very low densities. Examples are often large predators such as lions or bluefin tuna. About 10% of the threatened animal species that IUCN has assessed on land fall into this class, the remaining 90% of threatened species have small ranges (Pimm & Jenkins, 2010). The IUCN Red List is rapidly expanding its assessments of which species are threatened, but plants lag far behind vertebrates. At the time of writing (September 2020) only 43,000 plants had been assessed—about 10% of plant species.

The other way to answer this question is to combine what we know about plant species distributions—which is very limited—with what we know habitat changes, which we know in exceptional detail. There is a variety of threats. Habitat loss is the major concern;
but, for plants, introduced species and collecting are also serious threats. Climate disruption threatens species because it forces them to higher elevations in the tropics, where generally there is less space for them (Pimm, 2009). Enquist et al. (2019) analyse the integrated Botanical Information and Ecology Network (http://bien.nceas.ucsb.edu/bien/). These data are composed mainly of herbarium collections, ecological plots and surveys, and trait observations. They aim to standardize for effort to and map species with three or fewer records. The resulting maps are 1° resolution (approximately 100 by 100 km). Those maps strikingly confirm Myers’s hotspot classification and closely match 10 by 10 km maps of vertebrate endemism (www.biodiversitymapping.org; Jenkins et al., 2013). Central America, the Northern Andes, Madagascar, southwestern Australia, and the knot of mountains of the eastern Himalayas of Bhutan, Nepal, India, Myanmar, and southwestern China are well-known areas of endemism. More surprisingly, Enquist et al. suggest that existing knowledge has errors of omission: Northern Iran, Georgia, and Turkey have concentrations of rare species as does the Iberian Peninsula. Figure 2 also suggests that these areas may be species-rich.

In contrast, Enquist et al. do not pick up concentrations of rare species in coastal Brazil, or the Western Ghats of India. There could be several reasons for this. They are concerned with the fraction of species that are rare: these places may have many rare species in absolute terms, but relatively unexceptional numbers given their total species diversity. Second, there is the size of the sampling unit. The approximately 1 million km² of coastal Brazil’s moist forest has exceptional numbers of endemic plants. It is the fifth most important hotspot in terms of endemic plant species, with 3%-4% of all plant species occurring only there (Joppa et al., 2011; Myers et al., 2000). That said, its forests need not be exceptional at the scale of 10,000 km².

Given that we do not know some fraction of all plant species, can we decide whether these unknown species are likely to be threatened? They are likely to have small ranges and to be rare within them. (That is why we have not found them yet). There are fascinating exceptions (Mabberley, 2009;) and much depends on where these missing species live.

1.5 | What is happening to the places where rare species live?

How well can we map threats to species? For habitat loss, the answer is now "very well indeed." As inspection of Google Earth confirms, remote sensing provides satellite images globally and very frequently often at a resolution that allows individual trees and bushes to be seen. Even before such imagery was available, Myers recognized that human actions were malevolent. Those areas with the highest concentrations of small-ranged species are where habitat destruction is greatest. He defined biodiversity hotspots in terms of the collision of these concentrations with high levels of habitat loss. Remote sensing does not map introduced species, of course, but it does follow many of the consequences of global warming.

Twenty years ago, the best remote sensing technology was 30m resolution Landsat, a single image cost $2,000 and sharing images between researchers was prohibited. The conservation community pleaded for free global coverage of geo-referenced cloud-free imagery for 1990 and 2000. In early 2001, the then National Aeronautics and Space Administration (NASA) Administrator Daniel Goldin agreed. (Personal correspondence between author and Goldin, 1st January 2001.) Google Earth soon followed. Very high-resolution imagery at frequent intervals is now the norm, sometimes allowing the identification of individual trees. Silvery-leaved Cecropia stand out in the image in Figure 3, for instance. There are daily assessments of fires (https://earthobservatory.nasa.gov/global-maps/MOD14A1_M_FIRE). We can now follow regular changes in tropical forest cover (which fires often cause), following classic work by Skole and Tucker (1993) and other land uses (https://earthdata.nasa.gov/learn/user-resources/lcluc-information). Remote sensing allows the mapping of advancing tree lines (Harsch et al., 2009), of melting glaciers and the increasing numbers of transient wetlands formed as a consequence (Xu et al., 2019), and of other consequences of how human actions disrupt the global climate.

Such data now allow analyses of specific threats to biodiversity hotspots, such as expanding oil palm plantations (Vijay et al., 2016) and coca crops (Dávalos et al., 2011). They can also well address more general topics, such as whether protecting areas prevents deforestation (Joppa et al., 2008) or reduces fires in the Amazon basin (Adeney et al., 2009).

1.6 | What do we need to know better to permit more effective conservation of plant species?

Assuming that we had detailed answers to the previous questions, what are we doing to protect species? How well does the existing network of protected areas encompass species, especially those with the smallest ranges? Does that network allow for species moving upslope as the climate heats up? Given what we know, what can we do better, and how would better information about plant species improve our actions? An obvious first step would be to complete the taxonomic catalogue of plants, emphasizing places where species description rates per taxonomist remain high. These are where small-ranged species concentrate, where models predict that there will be many more such species, and of course, such species are most likely to be threatened. Such efforts would require targeted exploration, of course, but surely require more taxonomists, particularly those from the countries concerned, to achieve the task.

We also need substantially better knowledge of where rare species live. Enquist et al.’s impressive total of ~35 million quality records for ~400,000 species compares to half a billion records of 10,000 species of birds on the crowd-sourced eBird platform (www.ebird.org). Citizen science projects, such as iNaturalist (www.inaturalist.org), are an important innovation, with the number of records expanding past one million per month.
FIGURE 3  Bottom: aerial view of landscape east of Rio de Janeiro, Brazil. Top left: satellite image of area west of Rio de Janeiro in 2007; top right: drone image of same area in 2018. Bottom and top right photographs: Stuart Pimm; satellite image: Google Earth
Plants are not birds; their identification can pose challenges even to experts. Data quality is an issue: Enquist et al.'s analysis starts with 200 million observations, then excluding those with errors that are known to be common in citizen science data (errors in taxonomy, identification, and geographic coordinates). The data from iNaturalist and eBird that enter global databases are filtered by experts to verify them. Citizen science platforms provide help for the beginner and build an ever-growing cadre of nominal amateurs who may nevertheless have sophisticated identification skills. Such efforts can also identify where species should not belong—introduced species that if not controlled, can wreak havoc. These efforts can also monitor the elevation ranges of species and enable us to see which ones are moving upslope or to higher latitudes as the climate heats up.

With this information, we might address questions that we can routinely answer for (especially) birds, but also other terrestrial vertebrates. As described below, I chose two examples at extreme spatial ranges: global, and a small regional intervention in a biodiversity hotspot.

1.6.1  Setting global targets

How much habitat remains within a species range? How much of that range is protected and how much of it is within areas where the human footprint—a technical measure—is low (Pimm et al., 2018)? We know that the world's protected areas are disproportionately in places where people are not. They are often in very cold or very hot places (Figure 4).

This predilection for remote places has led to suggestions that the distribution of protected areas does a poor job of protecting biodiversity. Elsewhere, my colleagues and I (Pimm et al., 2018) argue that this misses a vital subtlety. Suppose we ask what fraction of species ranges should be protected by the ~13% of the ice-free land surface that protected areas cover. The null hypothesis is 13%, of course, but how does this vary with the size of the species range? We show that for species with large ranges, it does as expected. Indeed, for the very largest ranges, it must. To our surprise, we found that the existing global protected area network protects 30% or more of the ranges of birds, mammals, and amphibians with ranges of 1,000 km² or less. This result has policy consequences as I discuss below.

1.6.2  Practical, local interventions

Figure 3 shows an aerial view of coastal Brazil about 50 km east of the city of Rio de Janeiro. These lowland forests are massively fragmented. Saving Nature, (www.savingnature.com), helped its local Brazilian partners acquire land that, when reforested, established a habitat corridor to a previously isolated nature reserve (Pimm & Jenkins, 2019). To what extent did existing knowledge of biodiversity guide the choices that this project made?

It did so, but only in very broad terms. The land lies within a major biodiversity hotspot (see above). Increasing knowledge will likely add substantial numbers of new endemic plant species and is rapidly expanding the numbers of known animal species (Pimm et al., 2010). This is the case even for birds, which are the best-known taxon, and which include species described only after they became extinct (Lees & Pimm, 2015). We most certainly do not have detailed maps of where the thousands of known endemic plants live within this region. None of these uncertainties seriously challenge our reasons for working in the coastal Brazil hotspot.

But why this particular place? My colleagues and I also chose this area because it reconnected a previously isolated nature reserve. Fragments are bad for species in at least two ways: in themselves because the populations within them may be too small to be viable and because the intervening pastures impede forest species that need to move upslope as the climate heats up. Reforesting cattle pastures to establish connectivity would seem to be prudent for the area's plant species, even if we do not know precisely what they are, where they occur, or which animal species are their pollinators and seed dispersers.

2  CONCLUSIONS: CAN CONSERVATION SCIENCE DO BETTER?

The two examples discussed in the previous sections suggest answers to the key question of what we can do better. First, in 2021,
the Conference of the Parties to the Convention on Biological Diversity will meet in China to discuss future priorities for conserving biodiversity. Asking for numbers drawn from thin air—say protecting 30% of the planet—is not merely pointless, but potentially disastrous. Defining targets by area will encourage governments to do more of the same—create large, remote parks with relatively few species in them. Pimm et al. (2018) show that expanding the existing protected areas to 50% of the planet with the lowest human densities would achieve little in protecting the most vulnerable species of vertebrates.

We do not have this information for plants. It is an existential question, for we need to know how well the existing protected area network works in protecting the most threatened plant species. Would having that information make a great difference? I doubt it because I suspect that the small protected areas that do such an unexpectedly good job of protecting animal species with small ranges do likewise for plants with small ranges.

Second, the specific example makes a general point. Coarse-scale knowledge of plant endemism plus detailed remote sensing of remaining habitats encouraged practical conservation actions. Their details had much to do with local circumstances. Connecting habitats to allow species to move upslope is sensible, even if we know relatively little about the species involved. Would detailed knowledge of the area’s plant species and their geographies have caused us to do things differently? I doubt it. Nonetheless, it might have expanded the list of places we consider important. I have asked whether our knowledge of this region’s rich orchid flora is sufficient for their effective conservation (Pimm, 2005). It is not. Locality data are too sparse and do not immediately answer such basic questions as whether the region’s montane cloud forests should be a higher priority than the lowland forests.

A lack of knowledge must not prevent us from actions needed immediately. That said, the question of how protecting plants would lead to different decisions, both globally and locally, remains a nagging one. Simply asking for “more studies” is trite. Articulating what kinds of studies might change current conservation practice is prudent.

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