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Detecting early-warning signals of concern in plant populations with a Citizen Science network. Are threatened and other priority species for conservation performing worse?

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Abstract

1. Long-term monitoring of biodiversity is a fundamental part of environmental management, and Citizen Science (CS) approaches are increasing their contribution to such endeavour. CS plant monitoring programmes, however, almost exclusively report on the species presence, which can be used to detect changes in distribution or occupancy areas, but not to assess their local extinction risk. To anticipate the collapse of local populations, we need information on population sizes, trends, temporal fluctuations and threats. This is particularly important in the case of priority species (threatened, endangered and those that need special protection).
2. Here we describe the working protocol of the 'Adopt a plant' programme, a collaborative network that is currently monitoring 332 populations of 204 plant taxa (threatened, of community interest, common, rare and habitat indicators) across a heterogeneous landscape in NE Spain. Coordinated by scientists, participants estimate population sizes, record disturbances and follow scientifically rigorous sampling methods to track plant abundances year after year in fixed representative areas within populations. Two simple indices are estimated from that information: the overall trend (*mean population abundance change*, as percentage; PAch) and temporal fluctuations (*standard deviation of annual changes*; $PAch_{sd}$).
3. The potential of this ongoing high-quality dataset is demonstrated through the analysis of 242 populations monitored over 3–10 years. Stability is the dominant trend (mean PAch: +0.14%), with priority species having similar PAch and lower $PAch_{sd}$ than non-priority ones. Regardless of the priority status, small populations performed worse than large ones. Only 8% of studied populations faced direct human threats.
4. *Synthesis and applications*. The 'Adopt a plant' collaborative monitoring programme was launched in NE of Spain to produce standardized indices of abundance change and other early-warning signals of concern or risk of population collapse. Such information is crucial to report the conservation status of threatened plants, and plants of Community interest (Habitats Directive). By analysing hundreds of populations, we found that priority plants experienced few threats and did not perform

worse than non-priority ones. This unexpected finding evidences the importance of gathering massive demographic information to refine conservation priorities and to achieve a more comprehensive assessment of flora's vulnerability.

KEYWORDS

endangered and threatened plants, long-term monitoring, population abundance change, population size, structured data, temporal fluctuations, threats, volunteers

1 | INTRODUCTION

We are facing unprecedented rates of biodiversity loss and extinction rates at planetary scale (IPBES, 2019). Species' extinction begins with the loss of local populations that result from habitat destruction or demographic decline, often promoted by stochastic or deterministic factors (e.g. genetic drift or land-use changes). However, local extinctions are rare events that pass unnoticed for most species, which hinders our ability to adopt timely management strategies. Small population sizes, and negative or highly fluctuating population trends often precede local extinctions, and therefore constitute early-warning signals of population collapse or habitat impairment. For that reason, these variables are considered important criteria for identifying species of concern in the IUCN Red list process (IUCN Standards and Petitions Committee, 2019). This type of information can only be gathered through large-scale, long-term monitoring programmes (Pereira & Cooper, 2006), and is therefore not available for most species and populations.

Citizen Science (CS) programmes can play an invaluable role in obtaining information on the conservation status and trends of species. The contribution of volunteers has greatly increased in the last decades and is now a powerful tool in addressing major conservation challenges, providing up to 70% of species records (Chandler et al., 2017). Volunteers are also key for maintaining large and long-standing monitoring programmes (McKinley et al., 2017) that can be used to estimate global indices of population trends, such as the 'Living planet index'. This index combines data from repeated censuses of thousands of vertebrate populations globally (WWF, 2020) and has repeatedly indicated alarming declines.

Empirical evidence of decline, however, is not equally available for different taxonomic groups because monitoring programmes are largely biased, with up to 83% of CS projects focusing on animals (Buckland & Johnston, 2017; Burns et al., 2018; Chandler et al., 2017). Meanwhile, other highly abundant groups like plants are systematically underrepresented. The greater difficulty of taxonomical identification of plant species (of which there are many more than vertebrates) and their lack of movement might have made them less attractive for CS programmes. Plants, however, are structural elements of habitats and have an important contribution to the overall biodiversity and ecosystem services, making them particularly suitable indicators for global monitoring programmes (Pereira & Cooper, 2006). In addition, plants constitute an important part of the lists of threatened, or of high-conservation value species, and they must be periodically assessed at regional, national or supranational level. Article 17 of the Habitats Directive, for example, requests Member States of the European Union to report every 6 years on the conservation status of species and habitats of EU Community interest.

We present here the working protocol of a long-term participatory monitoring programme aimed at characterizing the conservation status, and assessing the potential extinction risk, of a wide variety of plants. It was designed to detect early-warning signals of poor performance or high vulnerability, based on three sources of information: (a) population size (small populations face higher extinction risk; Matthies et al., 2004), (b) temporal changes in population abundance (decline rate and environmental stochasticity are intrinsically bound to extinction risk; Menges, 1992) and (c) observed threats (directly linked to declines). The protocol was developed for the 'Adopt a plant' CS programme (AP; https://biodiversidadipe.csic.es/ciencia_ciudadana.html) which, to the best of our knowledge, is unique in terms of the careful scientific design used, and the detailed information obtained by non-professional people. Launched in 2010, its objective was to track the overall dynamics of plant diversity, with emphasis on threatened and 'rare plants' at global scale such as endemics. Following scientifically robust sampling designs, volunteers and rangers monitor plant populations across a wide range of habitats in the NE of the Iberian Peninsula (Aragón region), from semi-desert valleys to Mediterranean mountains and alpine summits.

Our aim here is threefold: (a) to provide guidelines for non-professional participants to set field sampling designs to gather long-term structured demographic data in a heterogeneous group of plants; (b) to demonstrate the potential of these data by testing if population size, trends and temporal variability of priority plants are lower compared to non-priority plants and (c) to assess threat frequency and potential effects on the population dynamics of priority and non-priority plants. We believe that extensive programmes like ours can help scientists to validate ecological and conservation biology paradigms, and improve conservation planning by managers and policymakers. To this end, we discuss the potential to expand this protocol globally.

2 | MATERIALS AND METHODS

2.1 | Selection of species, populations and habitats of interest

Three groups of plants of interest were defined. We first identified conservation priority plants following regional, national or international official lists. This group includes threatened species (critically endangered, in extinction risk, endangered, vulnerable and sensitive to habitat perturbation), as well as those listed in Annexes II and IV of the Habitats Directive of the European Union (full list of plants in Appendix S1 in Supporting Information). Since our Institution holds an important herbarium, we have extensive and detailed information on plant distributions in the region. Common plants co-occurring with priority ones were also monitored when possible, to control for possible habitat deterioration affecting all species in the study area irrespective of conservation status, and because they contribute greatly to overall richness. A second group of target plants was selected according to their singularity or regional rarity. These included endemics of the Pyrenean range or of a small part of the Iberian Peninsula, and species occurring at their distribution range limit within the study area. All these can be considered of interest but not of conservation concern. Finally, a third group of species included indicator plants of a variety of non-forested habitats of the Habitats Directive (Annex I) that cannot be monitored through remote sensing, such as endorheic lakes, bogs, cliffs, shrublands in the subalpine belt or on gypsum soil in the lowlands, and highly diverse (sub)alpine grasslands. Because of their ecological specificity, many of them can be considered good indicators of climatic change (e.g. when very dependent of humidity) or land-use change (e.g. when occurring in habitats that are under slow transformation).

Specific monitoring sites ('monitoring units', hereafter MUs) were selected according to expert knowledge, the conservation status of particular plant populations (e.g. under some specific threat), terrain accessibility, and in some cases, participants' preferences (e.g. within a protected area, or proximity to their residence). MUs (*N* = 213 in total), range from 2 to 4 km^2, typically contain one or two species of interest (range: 1–12 plants), are distributed along a very large altitudinal gradient (139–2,837 m a.s.l.) and are often located within the European Natura 2000 network (69%; Figure 1).

2.2 | Monitoring protocol

Once the MUs have been selected, the AP programme follows a four-step protocol.

1. **Characterization of target plants or habitats**. In the field, we start with a general inspection of the area of interest to identify

FIGURE 1 Distribution of Monitoring Units (MUs) included in the 'Adopt a plant' programme across the NE of the Iberian Peninsula (Aragón region; left upper), and examples of field survey methods used to monitor different kinds of plants in contrasted habitats (virtual plots in cliffs: bottom left); grids: lower middle; and macro- and micro-plots along transects: up and right)

the limits of the population of target plants, environmental heterogeneity and potential threats. During this inspection, participants are trained to distinguish target plants from similar ones nearby, as well as their different phenological states (e.g. juveniles vs. reproductive plants). Then, we define the extent of the population (area covered) and/or population size (number of plant units) according to the following ranges: small (<100 plant units or <100 m^2 of extent if plant units cannot be counted); medium (100–1,000 plant units or 100–1,000 m^2) and large (>1,000 plant units or >1,000 m^2). When individual plants can be counted, both flowering and non-flowering plants count, but seedlings are excluded. Sometimes, and due to the difficulty of distinguishing vegetative parts in dense areas or in the case of orchids, only flowering plants are surveyed. When the number of units and total area covered result in different categories of population size, area is chosen over number of units. All this information, plus additional data recorded in the field such as how to get to the population, or threats according to the HD or the IUCN unified classification of direct threats ('*proximate human activities or processes that have impacted, are impacting, or may impact the status of the taxon*'), is recorded in a 'fieldwork control protocol' (Appendix S2).

2. **Selection of the sampling design for repeated surveys through time**. Small populations can usually be surveyed in a relatively easy way. However, populations are often large in terms of number of plants or extension, and need sampling designs to be accurately surveyed every year (e.g. many juvenile individuals can be easily overlooked). To minimize the observation error, we sample in fixed representative areas (see examples in Figure 1 and more details in Appendix S3).

Table 1 shows the general rules to select appropriate plant abundance estimation methods (counts, presence or plant cover) and type of permanent sampling units. Such units go from macro-plots of hundreds of m^2 to micro-plots of 20×20 cm evenly distributed along transects (usually 10–50 meters long), or 10×10 cm miniquadrats in grids. For cliff-dwelling species, we use 'virtual plots' where individual plants are counted, by drawing fixed areas on good-quality digital photos that are surveyed every year by eye or aided by binoculars (see the bottom left picture in Figure 1). For very small and uncountable plants forming very small population, we estimate the gain or loss of occupancy area by comparing pictures through time. For count-based surveys in medium to large populations (~74% of monitored populations, Table 1), we add sampling units until a minimum of 300 plant units are counted. More than 1,000 records are usually used for presence surveys (~21% of monitored populations), and hundreds for plant cover surveys (4%) in highly replicated micro-plots along transects. To minimize observation error, we adjust the size of sampling units to the plant size and density, to include less than 30 plant units per plot if possible. For presence surveys, the number and distance between micro-plots along transects are adjusted for total records to fall within the range (20%–80%) of presences so that small changes can be detected between years. Sampling design (number of plots or transects and their distribution in space, size and distance of micro-plots along transects, etc.) is usually conducted in situ by an experienced scientist in agreement with the team of volunteers or rangers. This is because the design must be guided by two principles: (a) being as simple and effective as possible so that participants will be able to complete surveys on their own in just one working day, for a minimum period of 10 years and (b) being scientifically robust, to produce trustable indices based on the data gathered. Nevertheless, new MUs are established sometimes by participants, who must decide the sampling design on the go following suggestions of Table 1, or with our remote assistance. Anyway, the final sampling method can be adjusted (increasing or reducing sampling effort) from the second year. Each sampling design is thus unique and specific to each MU in terms or number of sampling units, micro-plots along transects, etc., because of such adjustment. A variety of examples and suggestions to set the sampling method are provided in García, Sanz, et al. (2019).

To ensure the successful finding of sampling units in the following years and facilitate the work of participants, we prepare a MU-specific *dossier* including all relevant information: GPS coordinates of each plot or transect, pictures showing all permanent marks or other spatial references used, pictures of the target plants, sampling gear, and decisions made during the monitoring (e.g. plant unit definition, whether to count individuals on the plot edge, etc.; see Appendix S3). This information guarantees the consistency of the sampling by unassisted volunteers over the years.

3. **Data recording and submission**. Participants are requested to conduct plant surveys yearly in similar dates (±15 days) to avoid phenological bias, over at least 10 years. This is the time span recommended by the IUCN Standards and Petitions Committee (2019) for priority species, and the minimum needed to consider the monitoring Long-Term Ecological Research (Lindenmayer & Likens, 2010). To facilitate the recording of plant abundance in the field, we create ad-hoc spreadsheet forms that mirror the specific sampling design in the field (plots or transects, including all micro-plots and miniquadrads where data are recorded; see Appendix S3); these automatically produce numerical summaries in tables and figures to visualize changes in abundance per plot or transect, and the whole population. Once filled, participants submit spreadsheets to us for validation. To estimate observation error and improve the accuracy of the index of abundance change, participants are requested to repeat the monitoring twice in at least one year throughout the 10-year period. Since this information is not yet available for all MUs, we have not included it in this study.

Along with annual records, participants also record observed disturbances (e.g. grazing, natural habitat succession). Later on, we decide which ones can be considered pressures or threats according to the HD.

TABLE 1 Guidelines for establishing sampling designs of the 'Adopt a plant' CS programme in the field, considering several variables of the plant species, population and site. 'λ_g': Geometric mean of annual lambdas; 't': survey year; 'tr': number of years between first and last survey minus one. % Monitored populations refer to the percentage being monitored under each kind of method

Type of survey	Population size	Plant detectability/ patchiness structure	General design	PAch index	% Monitored populations ($N = 332$)
Counts of units: individuals, ramets, clumps, reproductive plants	Small ($N < 50$–100 units and/or area <100 m^2)	—	Counts in (macro)plots. Variable size/length, subdivided if necessary to census plants easily (<30 plants per subplot). Extending outside the occupancy area to detect expansion. Most plants of the population (or all) will be recorded	$(\lambda_g - 1) \times 100$	73,6%
	Medium to large ($N > 50$–100 units and/or area >100 m^2)	—	Counts in long, rectangular (macro)plots (in low-density populations) or along transects (in very large or high-density populations). Variable lenght, number of micro- plots along the transect, and distance between them adjusted to avoid spatial autocorrelation if patchy distribution	$(\lambda_g - 1) \times 100$	
	Special cases: virtual plots on cliffs, sometimes with binoculars	—	Counts in plots drawn on pictures taken at distance. Plants can be drawn on maps, or censuses can be carried out with binoculars when necessary	$(\lambda_g - 1) \times 100$	
Counts of units are not possible or very difficult	Small area (<100 m^2)	High detectability because of high patchiness	Occupancy area estimated by means of GPS, or flags + pictures (repeated from the same point)	(Δ area) exp(1/tr)	0,09%
		Low detectability and/or low patchiness	Records of 'presence-absence' in grids containing many small (10 × 10 cm) units	Arithmetic mean $[(N_{t+1}) - (N_t)]$	21,3%
	Medium to large area (>100 m^2)	—	(1) Either 'presence-absence' or plant cover in ranks (from 0 [0%] to 4 [75%–100%]) in many micro-plots (ideally $N > 1{,}000$) along several transects. Size and distance of sampling units adjusted to get presence records within the range [20%, 80%], and reduced spatial autocorrelation. (2) Point intercept along a ruler for experts	Arithmetic mean $[(N_{t+1}) - (N_t)]$	4,2%

4. **Data validation and estimation of trends and fluctuations**. We check all annual data spreadsheets they send to us, to make sure all requested fields are filled correctly, and contact participants if necessary (e.g. missing/suspicious data or large fluctuations in population trends). After validation, we calculate the annual change of abundance every two consecutive years for each monitored species (only paired sets of plots or transects in consecutive years are used). This is calculated in two different ways, depending on the type of data. For monitoring based on counts of plant units, we use the ratio of counts, or lambda ($\lambda = N_{t+1}/N_t$, where N is the number of plant units recorded in years t and $t + 1$). When counts are not possible, we calculate the difference in the number of records of presence, or total plant cover area. Annual changes through the temporal series of monitoring are then averaged as the geometric mean for lambdas (λ_g; Elderd et al., 2003), or the arithmetic mean for records of presence or plant cover (Table 1), and transformed into percentages (as $(\lambda_g - 1) \times 100$ in the case of lambdas). The standard deviation of annual changes is also calculated. Thus, for each plant population having abundance data in several pairs of consecutive years, we estimate the *mean population abundance change* (PAch), and its temporal variation ($PAch_{sd}$), which allow a straightforward comparison among populations.

2.3 | Statistical analyses

Data gathered were analysed to look for three signals of weakness or bad performance: small populations, and negative or highly fluctuating trends. Given that species differ in their conservation status, our primary hypotheses were that priority species are more prone to show them, or suffer more threats.

Since population dynamics might vary across years and we are interested in overall and comparative results, we cleaned the dataset prior to analysis. We first removed MUs with less than 3 years of surveys and/or extremely low population sizes (<20 individuals), as these might be severely affected by demographic stochasticity. We also excluded species monitored by counting only flowering individuals (flowering does not necessarily correlates with the dynamics of the whole population) and annual plants (their dynamics are extremely dependent on stochastic climatic factors and therefore require very long-term series, not yet available). Our final dataset for the analysis of trends and fluctuations contained 242 plant populations of 150 taxa, and a total of 942 transitions (annual changes between consecutive years; range: 3–10 surveys per MU; median: 4).

We first analysed the association between population sizes and priority status with a contingency table and Chi-squared test (see also Appendix S4 for the same analysis but using random samples of same size). To test whether priority species are more prone to decline or fluctuate than non-priority ones, we fitted linear models with PAch and $PAch_{sd}$ as response variables, separately. Residuals of both linear models showed non-constant spread of variance, thus indicating violation of the homogeneity assumption (Appendix S5 and Figures S1 and S2). By plotting residuals against each explanatory variable of the models, we found differences in the spread of residuals between levels of priority, as well as across levels of population sizes (Figures S1 and S2). As data transformation was not sufficient to overcome heterogeneity problems, we fitted a generalized least squares (GLS) model with a residual variance structure (Zuur et al., 2009). Along with the two categorical variables (priority status and population size) and their interaction, we included in our initial model three other covariates: data type (counts/presence/plant cover; included to account for the possible effect of the method used to estimate abundance), number of transitions over which the response variables were averaged (to account for the robustness of the mean trends and temporal fluctuations, and the possible 'learning' effect of participants if they became more skilful the longer the temporal series was) and the elevation of MUs (to account for the fact that species tend to show more stable dynamics at higher elevations; Morris et al., 2008). In preliminary analyses, we also explored the possible dependency among observations of the same habitat using habitat type as a random intercept in a linear mixed model with the same fixed components. We selected a GLS model over a mixed model because dependency between observations was negligible between different habitats and sites (intra-class correlations were both close to 0). Following the protocol outlined by Zuur et al. (2009), we started with a saturated GLS model without variance structure. This model was then compared to models with different variance structures using Akaike's information criterion (AIC; Table S1). For covariate selection, we compared nested models fitted by Maximum Likelihood (ML) estimation using log-likelihood ratio tests (Zuur et al., 2009). The final model was refitted using Restricted Maximum Likelihood (REML) to reduce bias in the estimation of the variance components. The same procedure was repeated with temporal fluctuations or $PAch_{sd}$ (Figure S2). Models were fitted using package NLME (Pinheiro et al., 2020) in R v.3.6.3 (R Core Team, 2020). Pairwise comparisons between levels of population size were done using the post-hoc Tukey correction with R package MULTICOMP (Hothorn et al., 2008). Finally, given that eight MUs of priority species also contained co-occurring common plants, we tested whether they differed in PAch using a paired t-test after checking that normality and homogeneity of variance assumptions were met.

The response variables were not phylogenetically structured (Appendix S6), and hence there was no need for controlling for the residuals being potentially non-independent due to the shared evolutionary history of monitored taxa (Felsenstein, 1985).

3 | RESULTS

The 'Adopt a Plant' programme is currently monitoring 332 populations of 204 different plant species (most species are represented by only one monitored population). They are distributed in 213 sites (MUs; Figure 1), of which 39% ($N = 83$) contain priority plants. The most frequent monitoring method is counts of plant units (74%), followed by presence in highly replicated micro-plots along transects (Table 1). The number of records per MU ranges between 1 (total number of plant units in a small population of a priority species) to 5,500 (presence or absence of a plant in the same number of grid cells along transects).

Monitored populations are mostly of medium to large size (large: 60%, medium: 27%, small: 14%). There is, however, a significant difference in the association between population size and priority status (χ^2 = 15.19, *df* = 2, $p < 0.001$; same significant result when random samples of similar size were used, see Figure S4), as priority plants tend to occur more frequently as medium and small population sizes than non-priority ones.

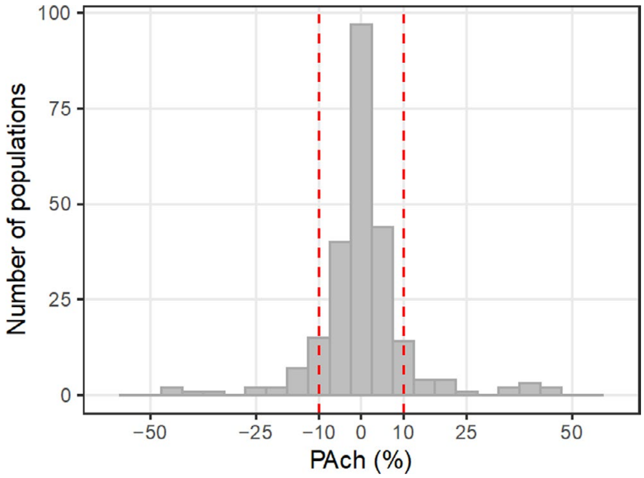

FIGURE 2 Frequency of mean annual population abundance changes (PAch) of 332 populations monitored for between 3 and 10 years (see text for details on how the index was calculated). Red dashed lines delimit the range [−10%, +10%]

Regarding the temporal dynamics of populations (*N* = 242 selected for this analysis), PAch values ranged between −59.5% and +45.5%, with most (82%) within the range [−10%, +10%]. The median PAch value was positive and close to stability (+0.12%; Figure 2).

Allowing different variances of PAch per population size and priority status levels reduced significantly the observed heterogeneity in the original GLS model without variance structure (see AIC values of Table S1). The interaction between population size and species' priority status was not significant (likelihood ratio test: L: 0.85, 2 *df*, $p = 0.655$) and this term was dropped from the final model. Data type and number of yearly transitions were also dropped from the final GLS model, because their effects were weak and did not improve model fit significantly (likelihood ratio tests: L: 1.36, 2 *df*, $p = 0.508$, and L: 2.09, 1 *df*, $p = 0.149$). Model validation indicated no major problems. Five observations with very large residuals were detected, but their influence on parameter inference and interpretation was negligible (see Appendix S7). Coefficients of the final model indicate that PAch values did not differ between taxa of different priority status, but between populations of different size (Table 2). Large populations tended to have more positive PAch values than medium and small populations, though this was significant only in the large versus small comparison (Table 3); no significant differences were found between medium and small populations (Post hoc Tukey estimate: 3.612, *SE*: 2.524, *Z* value: −1.431, $p = 0.3153$). Priority plants showed a surprising stability for PAch, more homogeneous across population sizes (and in particular for small-sized populations) than

TABLE 2 Estimated regression parameters, standard errors, *t*-statistics and probability values (*p*) of the GLS model fitted to plant population trends (PAch) and temporal fluctuations ($PAch_{sd}$) in the 'Adopt a plant' Citizen Science programme. Large population size and non-priority taxa are the reference levels

Response variable	Covariate	Estimate	*SE*	*t*-value	*p*
Pach	Intercept	4.318	1.386	2.993	0.003
	Altitude	−0.002	0.001	−2.587	0.010
	Priority status				
	Priority	0.372	1.135	0.328	0.743
	Population size				
	Medium	−2.554	1.524	−1.675	0.095
	Small	−6.166	2.269	−2.717	0.007
$PAch_{sd}$	Intercept	1.424	0.214	6.652	<0.001
	Altitude	−0.0001	0.0001	−2.081	0.039
	Type of survey				
	Count	−3.049	0.152	−20.102	<0.001
	Plant cover	0.024	0.305	0.079	0.936
	Priority status				
	Priority	−0.521	0.178	−2.934	0.003
	Population size				
	Medium	0.09	0.211	0.429	0.668
	Small	0.974	0.245	3.970	0.001

TABLE 3 Post hoc comparisons to detect differences in population abundance change (PAch) and temporal fluctuations ($PAch_{sd}$) between levels of population size and type of survey, in the 'Adopt a plant' Citizen Science programme

Response variable	Covariate	Estimate	*SE*	*Z*-value	*p*
PAch	Population size				
	Small–medium	−3.612	2.524	−1.431	0.315
	Small–large	−6.166	2.269	−2.718	0.017
	Medium–large	−2.554	1.524	−1.675	0.207
$PAch_{sd}$	Population size				
	Small–medium	0.883	0.287	3.081	0.006
	Small–large	0.974	0.245	3.970	<0.001
	Medium–large	0.091	0.211	0.429	0.902
	Type of survey				
	Count-presence	−3.050	0.151	−20.100	<0.001
	Cover-presence	0.024	0.305	0.080	0.996
	Cover-count	3.074	0.278	11.070	<0.001

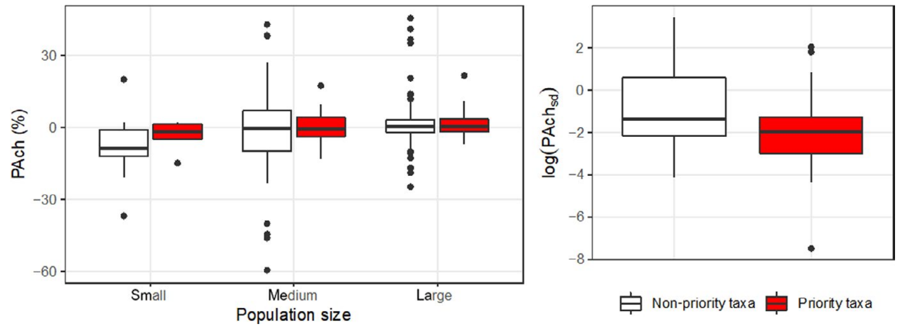

FIGURE 3 Boxplot of the mean population abundance changes as percentage (PAch, left) and temporal fluctuations ($\log(PAch_{sd})$, right), for populations of priority and non-priority plants of different sizes

non-priority plants (Figure 3). In the case of co-occurring common and priority plants, differences in PAch values were not statistically different ($t = 1.48$, $df = 7$, $p = 0.1833$).

The final model for temporal fluctuations (log-transformed $Pach_{sd}$) also included constant variance structures for population size and priority status levels (see Table 2; Table S1). In this case, temporal fluctuations in population abundance were significantly smaller in surveys based on count data than on presence or plant cover (Table 3). Once the effect of survey method and elevation was accounted for, we found that temporal fluctuations in priority taxa were significantly smaller than in non-priority ones ($p < 0.001$), though the effect size was not very large (Table 3). Likewise, we found that abundance changes in small populations fluctuated more than in medium and large ones (Table 3).

Only 8% of plant populations were directly threatened by human activities or processes, with agriculture (4.2%) and habitat shifting (2.4%) as main threats. The proportion of threatened populations was fewer within priority (5%) than non-priority plants (10%).

4 | DISCUSSION

In the current scenario of global changes, we face the double challenge of evaluating the conservation status and the dynamics of species and habitats to accurately forecast the fate of the most vulnerable component of biodiversity. Given the number of habitats, species and populations, however, this is a huge task that no administration can afford. The 'Adopt a plant' programme (AP) addresses that challenge through the involvement of volunteers and rangers in the collection of critical information related to the status, dynamics and threats of plant populations, by implementing scientifically robust sampling designs. Thanks to this working protocol we are compiling a unique long-term set of structured data to estimate trends and temporal variability of plant abundance within populations in a standardized way, allowing straightforward comparisons among populations. Together with population sizes and threats, these estimates constitute early-warning signals of concern classically related to population extinction risk, crucial information for effective environmental management (Bayraktarov et al., 2019).

4.1 | What makes the 'Adopt a plant' a unique Citizen Science programme?

Citizen Science programmes dealing with plants are frequent, but they often collect unstructured data such as local records, systematic monitoring of presence/absence (e.g. Martin et al., 2019; Pescott et al., 2015) or overall abundance for populations of rare and threatened plants (e.g. Barnard et al., 2017). Our AP programme collects structured data instead, following rigorous sampling protocols designed ad hoc for each target plant species. It is also unique in focusing on the dynamics of local populations, which we combine with population sizes and threats. Since the same team of participants is responsible for tracking the abundance of target plants year after year in each MU, the potential bias in data collection is minimized.

The two indicators of population extinction risk estimated from such information (abundance trend and temporal fluctuations), along with population size and distribution ranges, provide baseline information for the IUCN evaluation process and population viability analyses (Morris et al., 2002). These variables have been selected by Pereira et al. (2013) to detect environmental changes (Haase et al., 2018) and defined as an Essential Biodiversity Variables (EBV) to prioritize, standardize and facilitate comparisons. Hence, our methodological proposal is enabling us to compile the first extensive and well-structured dataset of these EBVs, of high value for conservation challenges.

Another important feature of our AP programme is that obtained trends are disseminated to participants on a regular basis in annual meetings, and to the general public through the webpage of the project (https://biodiversidadipe.csic.es/ciencia_ciudadana.html). They are also transferred to conservation managers for them to know the dynamics of priority plants so that they take actions if necessary, to avoid declines or extinctions, and fulfil national and international mandatory requirements.

The goal of many biodiversity-oriented CS programmes is to record species occurrences. This approach is becoming very popular thanks to the increasing possibilities offered by technological devices, software and platforms for the collection and exchange of biodiversity data (smartphones, apps, GBIF). These data have contributed to the development of distribution models in the last decade. However, short-term predictions of local abundance with real data are at least as important as modelling the long-term future distribution of species in hypothetical environmental scenarios (Ehrlén & Morris, 2015). A robust estimation of local abundance trends requires sampling designs adapted to each particular population, systematic fieldwork, and mechanisms to reduce and account for observation error. However, these types of designs are very scarce even among studies of endangered species (Bayraktarov et al., 2019; Morris et al., 2002). In fact, there are many demographic studies of plants based on structured matrix models, but they span short periods (<5 years; Salguero-Gómez et al., 2015) probably because of the high effort required both in the field and subsequent model analysis, as well as the lack of long-term stable funding. Methods proposed for the AP programme are adapted to people with no previous expertise, and generate data for robust estimation of future trajectories and to evaluate extinction risk (Elderd et al., 2003). Our methodological proposal, nevertheless, needs an important scientific investment, particularly at the onset of each monitoring (choosing the population of the target plant, setting the specific sampling designs, personal training of participants, data validation and mentoring over years; García, Silva, et al., 2019). Long-term species-specific fieldwork surveys like ours, however, will continue being the only trustworthy way of documenting real changes in the abundance of many small organisms like plants, and thus in assessing the trajectory and vulnerability of an important part of biodiversity.

4.2 | Assessing and comparing plant trends and vulnerability

In this study, we have shown how a Citizen Science programme can contribute to detecting population declines and associated potential threats, essential for effective biodiversity management. Contrary to expectations, our results highlight widespread stability of population trends for many different plant species in an environmentally heterogeneous European region, and very few threats, particularly for priority plants. This finding is in line with the increase in abundance of many plant species found in the European Alps over a longer period (more than 4 decades; Rumpf et al., 2018).

Another remarkable and novel result obtained from our AP programme is the evidence that trends of priority plants did not differ neither from co-occurring common plants nor from other non-priority plants in the region, casting doubt on the classical conservation biology tenet of worse performance of the former ones. In contrast, our results do support the general expectation that small populations perform worse irrespective of their conservation status (see also Matthies et al., 2004). We found that priority plants might not always be as vulnerable as thought at local scale when their populations are medium or large sized (the most common cases in our study). This finding suggests that estimating local population sizes should be the first and priority step for assessing potential vulnerability. In another large-scale analysis based on sporadic data gathered by volunteers, Lawson et al. (2008) found that small (<50 individuals) isolated populations were performing similar to large ones. These authors, however, acknowledged that a substantial proportion of unexplained variation was likely due to measurement error, a source of variation that we have minimized with our specific sampling designs.

The scarcity of threats and the overall stability found in monitored plants are probably associated with their frequent location in areas covered by the European 2000 Natura network. Whatever the reason, our results contrast with the overwhelming evidence of negative trends resulting from animal monitoring (e.g. Burns et al., 2018; Rosenberg et al., 2019; but see Wiens, 2016), and highlight the risk of accepting general rules and conclusions derived from studies with vertebrates to assess the conservation status and risk of other groups like plants (Knapp, 2011). Although our results are restricted to a single European region and are based on a relatively short temporal series (3–10 years), they result from analyses of more than 300 plant populations covering a broad variety of biological and ecological conditions: 3,000 m of altitudinal range, a wide habitat heterogeneity across Mediterranean and Eurosiberian biogeographical regions, and most life forms such as biannuals, perennial herbs, geophytes or shrubs.

In summary, contrary to classical surveillance monitoring, our AP programme meets the critical components of effective structured monitoring aimed at generating long-term, high-quality datasets that allow testing specific hypotheses (sensu Bayraktarov et al., 2019; Lindenmayer & Likens, 2010; Pescott et al., 2015). We tested here the presumed worse performance of threatened plants, and results demonstrated the benefit of moving away from a model solely focusing on them towards a more comprehensive approach for comparative purposes. Monitoring population dynamics constitutes the core of the adaptive management process, providing the necessary link between threats, objectives and management alternatives (Bakker & Doak, 2009; Bayraktarov et al., 2019; Lahoz-Monfort et al., 2014). Our AP programme also shows that mandatory evaluation requirements such as the Habitats Directive can be delivered with CS approaches. We therefore encourage conservation policymakers to implement this or similar approaches, and we advocate for its expansion and integration into larger national or international platforms. A larger-scale participative network would also allow conservation managers to share standardized information to better face current challenges in Biodiversity conservation. Long-term monitoring of non-priority species will also help to address question-driven large-scale analyses of trends and pace of biodiversity changes, considering different situations such as central and edge locations (the central–peripheral hypothesis), contrasted habitat types, different life forms or in protected versus unprotected areas. Comprehensive programmes involving citizen scientists and different kinds of plants will assist conservation policymakers to protect the most vulnerable species while managing other structurally important components of the communities within which they are integrated.

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AUTHORS' CONTRIBUTIONS

M.B.G. conceived the study, designed the methods and obtained the funding; I.P., J.L.S., P.T. and M.B.G. designed the sampling methods in MUs, coordinated, trained and mentored the participants, and validated the data; J.L.S. optimized the fieldwork forms for numerical and graphical validation; I.P. analysed the data together with M.B.G.; M.B.G. wrote the manuscript with the critical review of I.P. and inputs from J.L.S. and P.T.

DATA AVAILABILITY STATEMENT

Data available from DIGITAL.CSIC Repository: Plant population MONITO dataset 2010–2019. http://dx.doi.org/10.20350/digitalCSIC/13825 (García, 2021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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