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LETTER

Nationwide revisitation reveals thousands of local extinctions across the ranges of 713 threatened and rare plant species

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Abstract

Despite increasing awareness of global biodiversity loss, we lack quantitative data on local extinctions for many species. This is especially true for rare species, which are typically assessed on the basis of expert judgment rather than data. Revisiting previously assessed populations enables estimation of local extinction rates and the identification of species characteristics and habitats with high local extinction risk. Between 2010 and 2016, in a nationwide revisitation study, 420 volunteer botanists revisited 8,024 populations of the 713 rarest and most threatened plant species in Switzerland recorded between 1960 and 2001. Of the revisited 8,024 populations, 27% had gone locally extinct. Among critically endangered species, the local extinctions increased to 40%. Species from ruderal and freshwater habitat types showed the highest proportion of local extinctions. Our results provide compelling evidence for rapid and widespread local extinctions and suggest that current conservation measures are insufficient. Local extinctions precede and provide early warnings for global extinctions. The ongoing loss of populations suggests that we will lose species diversity unless we scale up species-targeted conservation and restoration measures, especially in anthropogenic landscapes.

KEYWORDS

citizen science, endangered plants, extinction risk, IUCN threat categories, monitoring, rarity, species trends

1 | INTRODUCTION

Biodiversity is declining globally (Ceballos et al., 2015; Convention on Biological Diversity 2018; Dirzo & Raven 2003) and is changing regionally and locally due to local extinction and colonization events (Dornelas et al., 2019; Finderup Nielsen, Sand-Jensen, Dornelas, & Bruun, 2019; Hillebrand et al., 2018). Despite progress in quantifying global extinction rates of species, large-scale *quantitative* information on *local* recent extinctions of populations is missing for many species (Balmford, Green, & Jenkins, 2003). This hampers generalizations about the patterns, habitats, and characteristics of the species that are in decline (Godefroid, Janssens, & Vanderborght, 2014). Particularly for rare and threatened species, estimates of trends have often been based on expert knowledge alone (Balmford et al., 2003; Batt, Morley, Selden, Tingley, & Pinsky, 2017). However, precise quantitative data on species and population losses are crucial for understanding species responses to past and future environmental change and for adequate conservation and restoration measures (Parmesan & Yohe 2003; Pereira & David Cooper 2006).

Local extinctions are usually nonrandom (Stöcklin & Fischer 1999; Vamosi & Wilson 2008) and may depend on species characteristics or on species' affinity to certain habitat types (Janssen & Rodwell 2016). Threatened species, that is, species with small areas of geographic distribution and declining, small, isolated, or fragmented populations, have a particularly high local extinction risk and have a low colonization ability as they are more sensitive to environmental and demographic stochasticity (Ellstrand & Elam 1993). These species are usually Red Listed and—based on several criteria such as size and decline of geographic range and populations—are classified into different threat categories evaluating their extinction risk (IUCN, 2001). Previous Red Lists for plants in Switzerland, and most other national Red Lists, have mainly relied on expert opinion to estimate a species decline in range or population size. Assessments have rarely been based on quantitative assessment of species change, due to the time and financial cost of population monitoring (Balmford et al., 2003). While it is likely that species which are assigned to the highest IUCN threat categories by experts are also the ones showing the highest local population extinctions under ongoing global change (Gaston, 1994; Ohlemüller et al., 2008), this widely accepted assumption has rarely been tested quantitatively.

We can identify local extinctions and species characteristics and habitats associated with high local extinctions by comparing old species lists with recent ones and revisiting sites with old species records (Lavergne, Molina, & Debussche, 2006; Shaffer, Fisher, & Davidson, 1998; Tingley & Beissinger 2009). Unfortunately, such studies are often confined to single habitats (Leach & Givnish 1996) or species (Lienert, Fischer, & Diemer, 2002), and lack comprehensive and precise data for threatened species. Most revisitation studies estimated extinction events based on very old initial records (Lavergne et al., 2006; Van der Veken, Verheyen, & Hermy, 2004; Walker & Preston 2006). Thus, data on recent local extinctions of several populations for many threatened plant species are lacking.

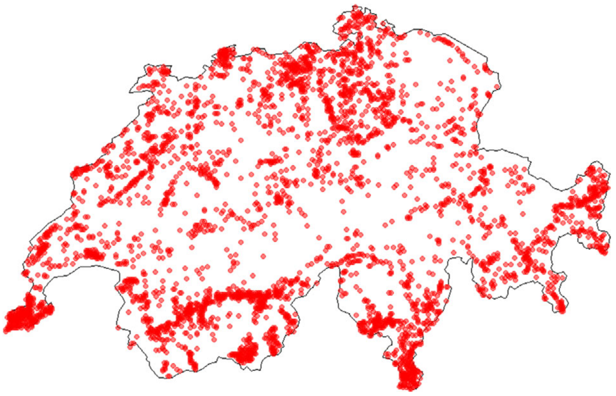

FIGURE 1 We launched a nationwide revisitation study in which 8,024 population occurrences of 713 plant species in 3,731 different 1 km × 1 km grid cells (red dots) were revisited throughout Switzerland

Here, we present a countrywide revisitation study, where the presence or absence of the 713 rarest and most threatened plant species of Switzerland were reassessed in 8,024 populations by more than 420 trained volunteer field botanists. This enabled a quantitative estimate of recent local extinctions for many species and habitat types throughout the whole country (Figure 1). It also enabled us to explore the relationship between species characteristics and local extinctions in order to understand potential drivers of population losses.

Specifically, we investigated (a) whether plants already considered to be heavily threatened based on the Red List in 2002 (expert knowledge) were more likely to have gone extinct locally; (b) whether species from certain habitat types had higher local extinction risk; and (c) which species characteristics were most associated with local extinctions.

2 | MATERIALS AND METHODS

To assess the magnitude of local extinctions, we launched a large revisitation project. This involved 753 plant species (713 species in final dataset, see below), including all species considered threatened in Switzerland in 2002 (all species in the IUCN categories "regionally extinct," "critically endangered," "endangered," or "vulnerable"), and rare species not yet considered threatened, but with a small range size, or data-deficient species (Text S1). For these, volunteer botanists revisited more than 8,000 localities based on old species records to check if the species was still present, covering sites throughout Switzerland (Figure 1).

2.1 | Selection of localities

To select localities to revisit, we used old species records (1960–2001) from *Info Flora*, an extensive national database of plant records in Switzerland from herbaria, monitoring programs, and botanists. We divided Switzerland into 1 km × 1 km grid cells. For each of the 753 selected plant species, we selected grid cells that contained records of the respective species between 1960 and 2001. We excluded entries before 1960 because these species trends would have mostly indicated historical changes beyond the scope of a local assessment based on IUCN Red List Guidelines. We chose 2001 to be the upper bound because the former Red List was established in 2002 (Moser, Gygax, Bäumler, Wyler, & Palese, 2002). Most of these "old records" were recorded between 1990 and 2001 (median: 1997). For each of the 753 species, we then selected populations to revisit (where a population corresponds to a record in a 1 km × 1 km grid cell): we selected all populations of species with fewer than 30 recorded populations (654 species in the final data set, Figure S1), and randomly selected 30 populations for species with 30 or more records (68 species).

2.2 | Reassessment of presence in formerly inhabited populations (2002–2016)

For all selected populations, we reassessed current presences or absences of a species in a grid cell to gain a quantitative estimate of species local extinctions. This was done in two ways. First, we checked whether any of the selected grids with old records were confirmed recently by a new entry in the national database of the Swiss Flora (2002–2016, entries after the release of the former Red List in 2002), and considered these confirmed records as populations with a current "presence" of a species (1,660 populations). As we considered the likelihood that these populations were still present at the start of the revisitation action as high, this allowed us to safe labor.

For the remaining 6,374 populations, *Info Flora* launched a large revisitation initiative. With the help of more than 420 trained volunteers, all excellent field botanists, all 6,374 populations were revisited during 2010–2016 and the presence or absence of a species in a grid cell was recorded. The volunteers carefully searched for their target species in the whole 1 × 1 km grid cell at a time of the year when the target species is flowering (Lauber, Wagner, & Gygax, 2018), until presence was either confirmed or considered as highly unlikely (Text S2).

A common difficulty in revisitation studies is distinguishing between true absences and nondetections. If a species is overlooked, its estimated extinction will be inflated. To minimize such bias botanists received as detailed a description as possible of the site of occurrence of a species. If a species was not detected, the sites were revisited several times, mostly by different botanists and at different times of a year. To avoid misclassifications of species, field botanists provided pressed plant material or photos of the target species, which were checked by expert botanists. Finally, we found that tall plants (max. height, obtained from Flora Helvetica) were not rediscovered more often than plants with a small statue, indicating that detectability was high.

Some populations turned out to be inaccessible ($n = 62$) and some had been assigned to the wrong grid cell as old records had imprecise coordinates. In a few cases, a species similar and related to the species of interest was found, suggesting that the species of interest had previously been misidentified. For three species, we lacked data on IUCN threat status and species characteristics (see below). We excluded these cases from the final dataset, leaving us with 8,024 grid cell-species combinations of 713 plant species. In some grid cells (1,515 grid cells), populations of more than one species were revisited, resulting in a total of 3,731 different 1 km × 1 km grid cells that had been revisited throughout Switzerland (Figure 1).

3 | STATUS OF THREAT AND CHARACTERISTICS OF HABITAT AND SPECIES

We used the IUCN threat status from the Red List of the vascular plant species in Switzerland from 2002 to evaluate species extinction risk (Moser et al., 2002). Among the species were also eight that had been classified as "regionally extinct" in the former Red List in 2002. Species were assigned to one or several habitat types according to Eggenberg et al. (2018). These were crop fields and vineyards, shorelines, bogs and mires, rocks and debris, dry meadows and pastures at low elevations, rich meadows and pastures at low elevations, alpine pastures, herbaceous fringe, shrubs and hedges, forests, ruderal areas, rivers, and lakes. Species could receive more than one habitat type classification (Text S3).

To characterize the competitive ability of species, we used maximum height (obtained from the Flora Helvetica, Lauber et al., 2018), and a competitive strategy classification (CSR-strategy of Grime, see Text S3). We used the degree of competitiveness (0, c, cc, ccc) as an indication of a species' competitive ability (where 'ccc' is the most competitive). We characterized species according to their ruderal strategy (0, r, rr, rrr, with 'rrr' indicating a fully ruderal life strategy). We classified the species according to the position of their realized niche optima along important environmental gradients, which are related to land-use intensity, using ecological indicator values: In Switzerland, land-use change was most drastic in the Lowlands at high temperature, and involved the destruction and degradation of mires and bogs. We therefore used the ecological indicator values for vascular plants for temperature, continentality, light, soil pH, moisture, and nutrients (Landolt et al., 2010, see Text S3). Finally, we recorded the number of years between the last record of a population and the start of the revisitation project (2010 minus year of last record, values range between 9 and 52 years, median 13 years).

4 | STATISTICAL ANALYSIS

To test whether plants already considered to be heavily threatened based on the former Red List in 2002 were more likely to have gone extinct locally, and to test whether local extinction occurred more often for plants from certain habitats or plants with certain characteristics, we used generalized linear mixed-effect models (lme4 package in R; Bates, Mächler, Bolker, & Walker, 2015). The response variable was whether or not a species was rediscovered in a certain grid cell (0,1).

First (Model 1), we included the threat status of our species (IUCN threat status 2002) as a fixed effect, the number of years since the last record of a population as a covariate (scaled), and plant species and grid cell as random effects. Second (Models 2), we included the habitat of the species as fixed effects, the number of years since last record as a covariate, and plant species and grid cell as random effects. Because species sometimes were assigned to several habitats, we ran one model for each habitat type (see Text S4). Third (Model 3), we included the degree of competitive strategy (0, c, cc, ccc), the degree of ruderal strategy (0, r, rr, rrr), maximum plant height (log transformed) and all indicator values (as continuous variables to better interpret model findings) as fixed effects, the years since last record as a covariate, and plant species and grid cell as random effects. All continuous variables were standardized to a mean of zero and a standard deviation of 1. We did all analyses in R version 3.5.3 (R Core Team 2013). We derived significance using likelihood-ratio tests comparing models with and without the factor of interest. Model estimates and 95% confidence intervals were obtained with the *effect* package.

5 | RESULTS

Of the 8,024 reassessed populations, 5,859 (73 %) were confirmed, whereas 2,165 (27 %) had gone locally extinct, providing compelling evidence that populations of threatened plant species in Switzerland are declining. The further in the past a population was recorded for the last time, the higher its proportion of local extinctions (last record in 1960 = 49% of populations extinct, last record in 2001 = 15% of populations extinct; Figure 2). Plant species with the highest threat categories according to the previous Red List (Moser et al., 2002, expert opinion) showed the strongest losses during the revisitation in 2010–2016 (Figure 3, Table S1, 40% of populations of critically endangered species extinct vs. 12% of populations of least concern species). Of the eight species classified as "regionally extinct" in 2002, seven of 31 populations of six species were rediscovered. None of the species had become nationally extinct. Populations of species from ruderal habitats such as crop fields and vineyards (46% of populations extinct) and trampled habitats and other ruderal areas (43% of populations extinct), and plants related to wet habitats, for example, rivers and lakes (32%), shorelines (31%), and bogs and mires (27%), showed two to three times higher proportions of extinction in the revisitation project than populations from other habitats (e.g., alpine pastures = 15% of populations extinct, forests = 16%, dry meadows and pastures at low elevations = 18%; Figure 4, Table S1). Accordingly, plant species with a higher moisture indicator value (from flooded, wet, and moist habitats) and species with a more ruderal life strategy had the highest proportions of extinction (Figure S2, Text S3). Plants with higher temperature values (from warmer climates in the lowlands), higher continentality values (with an continental climate, e.g., the canton of Valais), and lower reaction values (from acid habitats with a low pH) showed highest local extinctions. The nutrient value was positively related to extinction proportion, however this effect disappeared after we accounted for a confounding effect of ruderal life strategy

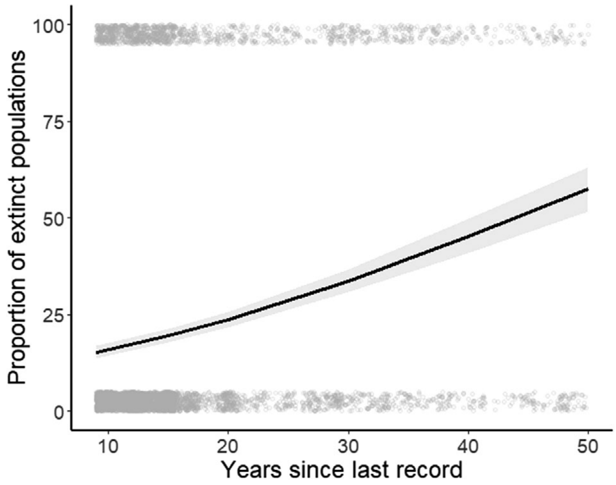

FIGURE 2 Proportion of extinct populations was highest the further in the past a population had been recorded for the last time (start of the revisitation project in 2010 minus year of last record). We show fitted values from a generalized linear mixed effect model (Model 1, Table S1), and shaded area represents 95% confidence intervals

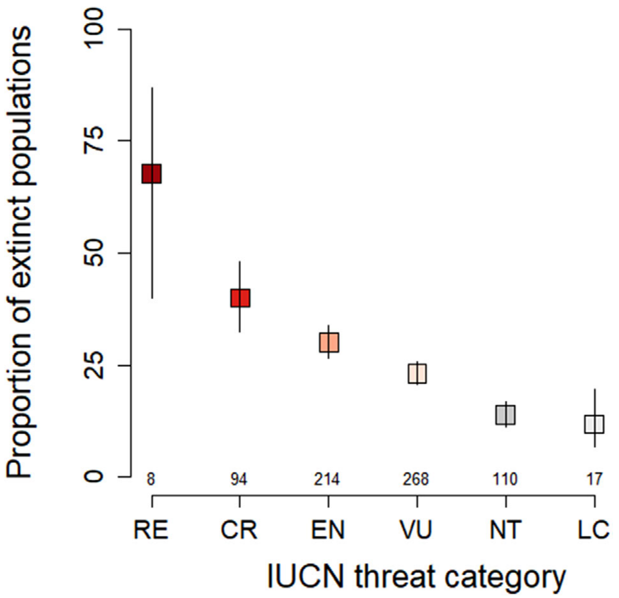

FIGURE 3 Proportion of local population extinction (populations that were not refound during the revisitation in 2010–2016) increased with higher IUCN threat category (classification based on expert knowledge in 2002, Moser et al., 2002; RE, regionally extinct; CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern). Two species assigned to the category *data deficient* were removed from this model. We show fitted values and 95% confidence intervals from a generalized linear mixed effect model (Model 1, see Table S1). The number at the bottom indicate the number of species in each threat category

(see Text S5, Figure S2, Table S1). The competitive strategy, the height of the plants, and the indicator values for light were not related to the proportion of local extinctions (Table S1).

6 | DISCUSSION

In this countrywide revisitation project, we reassessed the presence or absence of the 713 rarest and most threatened plant species in Switzerland in 8,024 populations. We show that overall 27% of the reassessed populations had gone locally extinct within the last 10–60 years, and that recent local extinctions were highest for the most threatened plant species. For example, critically endangered species lost 40% of their populations since 1960 (124 out of 303 populations extinct, Figure 3). Our study shows clearly that the current conservation strategy in Switzerland of habitat protection and management alone is insufficient to protect local populations of rare and threatened species. Without additional species-targeted conservation measures, which combine the restoration of habitats and habitat connectivity with measures such as species translocation or assisted migration, the most threatened species are highly likely to further lose ground.

Revisitation studies, as the one we present here, can detect extinction events but are not designed to analyze new species colonization events. Only plots with reliable data on a species' absence in the past can classify a new species record as a true colonization event. Such datasets have only recently started to become available (permanent monitoring plots), and rarely for threatened species. While it is conceivable that some of the declining species have established new populations elsewhere, we consider this highly unlikely, as their specific habitats are often rare and isolated (Delarze, Gonseth, Eggenberg, & Vust, 2015) and dispersal to suitable habitats is likely to be very limited.

Populations of species from ruderal habitats (crop field and vineyards, trampled habitats, and other ruderal areas) and plants related to wet habitats (rivers and lakes, shorelines, bogs, and mires) were two to three times more likely to have gone locally extinct than populations of species from other habitats (e.g., alpine pastures or forests, Figure 4, Table S1). This mirrors outcomes of the Swiss Red List of Habitats (Delarze et al., 2016) as well as the European Red List of Habitats (Janssen & Rodwell 2016), which both classified freshwater ecosystems, mires and bogs, and agroecosystems as among the most threatened ones. Freshwater habitats are experiencing drastic declines in biodiversity worldwide (Dudgeon et al., 2006; Living Planet Report based on mammals, birds, reptiles, and amphibians; WWF 2018). In Switzerland, freshwater and wetland habitats have been greatly reduced in quality and quantity due to pollution (e.g., nitrogen deposition), flow modification and the loss of dynamic processes, destruction or degradation, and conversion of habitats to agriculture and forestry (Delarze et al., 2016). The strong decline in populations of freshwater plants shown in our study underlines the urge for national strategies to balance the use of freshwaters (e.g., for farming and hydropower) and the conservation and restoration of freshwater biodiversity. Similarly, in Europe and particularly Switzerland, the quality and diversity of ruderal habitats in the agricultural landscape declined, as agroecosystems changed drastically since the 1950s due to an intensification of land use (Storkey, Meyer, Still, & Leuschner, 2012). Increased use of fertilizers and herbicides, a loss of microstructures in open landscapes, and improved cleaning of crop seeds are likely to be responsible for the observed decline in ruderal species. Taken together, the strong decline of freshwater species and species from extensive agroecosystems mirrors European trends in the threat status of habitats. Conservation should thus expand the restoration of cultural landscapes (Mayfield & Daily 2005). Strategies to increase the dynamics of freshwater systems, and incentives to enhance landscape structure such as hedges, stone walls, and other

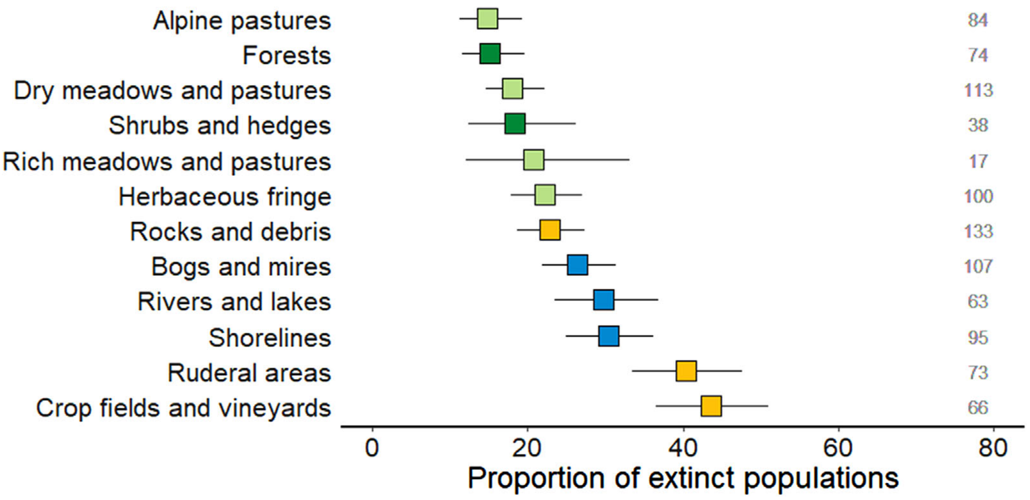

FIGURE 4 Species from agroecosystems, ruderal habitats, and wet habitats showed the highest proportion of local extinctions. We ran separate models for each habitat type with the covariate year since last record (scaled), and present the fitted values and 95% confidence intervals from generalized linear mixed effect models, for each habitat type. Yellow = ruderal habitats, blue = wet habitats, light green = grasslands and habitats dominated by herbaceous plant species, dark green = shrub and tree dominated habitats. The numbers to the right indicate the number of species in each habitat category

microhabitats in open areas are essential. Together with species-targeted measures, this may offer a great potential for the recovery of many threatened species in Europe.

Land use in Switzerland has undergone drastic changes in the middle of the 20th century, with an intensification of land use in the Lowlands, while alpine regions have continued to be used extensively. We therefore expected that plants growing in regions with warm or oceanic climate, as well as plants growing in nutrient-poor habitats (e.g., dry grasslands), are associated with the highest extinction probability. At the same time, many mires and bogs have been converted to agricultural areas or have experienced declines in habitat quality (BAFU Bundesamt für Umwelt 2007). Accordingly, we found that plants with higher temperature values (from warmer climates), higher continentality values (with a continental climate, such as in the Valais), and lower reaction values (acid habitats with lower pH, such as in bogs and mires) showed highest local extinctions (Figure S2, Table S1). This suggests that habitat change, loss, and destruction are important drivers of local population extinctions of rare species. This is in line with findings from biodiversity research that land-use intensification causes the homogenization of ecosystems, and results particularly in a loss of rare species (Finderup Nielsen et al., 2019; Gossner et al., 2016). Monitoring rare species and their populations is therefore important to assess the consequences of global change, especially land-use change, on our ecosystems, which are not captured sufficiently by temporal trends in species richness alone (Blowes et al., 2019; Dornelas et al., 2019; Hillebrand et al., 2018).

Our findings provide compelling evidence that local plant populations of threatened species in Switzerland are declining rapidly. Given the low number of remnant populations for most of these species (Figure S1), a further decline is likely to result in many nationwide species extinctions (Ceballos & Ehrlich 2002). As our quantitative assessment of population loss was very laborious and challenging, similar data are lacking for almost all other regions. We suggest that the combination of nationwide floristic data bases with comprehensive revisitation by volunteer botanists is a promising model also for other countries to assess species trends and to inform conservation and restoration (Butchart et al., 2004; Houlahan, Findlay, Schmidt, Meyer, & Kuzmin, 2000; Mace, 2005). Such a quantitative assessment provides an unbiased view on the state of threatened species and can detect rapid changes in species trends that may not be perceived by experts. This helps experts to reliably assign species to IUCN threat categories in Red Lists, and to execute conservation measures rapidly, if necessary.

Our study presents clear evidence that current efforts to conserve threatened plant species are insufficient to achieve national and international targets (Convention on Biological Diversity (CBD), 2011; Swiss Biodiversity Strategy 2012) for maintaining biodiversity. The current paradigm of protecting and restoring threatened habitats is failing to avert extinctions. Going forward, we need to develop a comprehensive landscape approach, involving the creation of ecological infrastructure and translocation and assisted migration of threatened species into suitable habitats.

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AUTHOR CONTRIBUTIONS

Andreas Gygax, Beat Bäumler, Christophe N. Bornand, Philippe Juillerat and Lionel Sager designed the revisitation project with input from Markus Fischer; Christophe N. Bornand, Andreas Gygax, Philippe Juillerat, Michael Jutzi, Lionel Sager and Stefan Eggenberg selected the populations and coordinated the revisitations, Anne Kempel analyzed the data and drafted the manuscript with substantial input from Markus Fischer, Andreas Gygax and Christophe N. Bornand, and all authors contributed to revisions.

DATA AND MATERIALS AVAILABILITY STATEMENT

Data and code related to the revisitation study can be found at https://doi.org/10.5281/zenodo.3901662

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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