Global Ecology and Conservation 30 (2021) e01785

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Control method that may limit an invasive plant in a protected area: Stem breaking decreases alien goldenrod performance and enhances pest attack

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ARTICLE INFO

Keywords:
Biological invasions
Protected areas
Pest-plant interactions
Pest load
Alien goldenrods

ABSTRACT

Developing alternative control approaches is particularly important for reducing the impact of biological invasions in protected areas. We present a simple stem-breaking control approach for alien goldenrod, *Solidago gigantea*. The method was tested at the Natura 2000 site 'Skawina meadows area' in southern Poland, where *S. gigantea* threatens the co-occurring protected and rare native species. The tests were performed over 40 days in 2012 and 2013 and involved hand-breaking of stems. Control and broken plants were surveyed in terms of their performance and pest pressure, and the number of pests attacking a given control and/or broken plant was assessed. We found that stem breaking may reduce *S. gigantea* generative reproduction potential by preventing seed release and increasing pest pressure. The dominant pest groups were Stylommatophora and Auchenorrhyncha. Application of this method in strictly protected areas does not require virtually any equipment and can be performed by non-qualified volunteers. Thus, the proposed approach may be an economic and environmentally friendly method of alien plant species control; however, further tests at a larger scale are needed to confirm this hypothesis.

1. Introduction

A recent assessment indicated that 5–20% of alien species become invasive (Jeschke, 2014), and the percentage of invasive alien species ('IAS') will increase in the future (Rumlerová et al., 2016). However, although the general negative impact of IAS on biodiversity and the human economy has been widely demonstrated (Bellard et al., 2016; European Commission, 2020; Pimentel, 2011), knowledge of how IAS impact protected areas ('PAs') is still limited (Foxcroft et al., 2013). PAs play an essential role in nature conservation at the global scale; thus, the control of alien species in PAs should be particularly promoted (Genovesi and Monaco, 2014).

An example of a PA affected by an alien species is Skawiński obszar łąkowy ('Skawina meadows area'), which belongs to the Natura 2000 network (no. PLH120079) and protects wet *Molinia* meadows and lowland hay meadows under the Habitats Directive (European Commission, 1992; Joyce, 2014). Four endangered butterfly species occur there: *Lycaena dispar*, *Lycaena helle*, *Phengaris nausithous* and *Phengaris teleius* (species included in Article 4 of Directive 2009/147/EC and listed in Annex II of Directive 92/43/EEC). Although not

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https://doi.org/10.1016/j.gecco.2021.e01785
Received 5 May 2021; Received in revised form 27 August 2021; Accepted 27 August 2021
Available online 1 September 2021

large (44.13 ha), this PA has a very important function in sustaining the integrity of the Natura 2000 network in southern Poland by ensuring a connection between other Natura 2000 sites. Since the 2010s, this area has been threatened by the invasion of the giant goldenrod, *Solidago gigantea* Ait. (Asteraceae).

S. gigantea is a perennial herb introduced from North America in the 18th century as an ornamental and melliferous plant (CABI, 2020). It is a highly invasive alien species in southern Poland, as in most European countries, and poses a serious threat to native biodiversity and ecosystem functioning. The species outcompetes native plant species (e.g., due to its allelopathic ability; Baličević et al., 2015) and negatively affects aboveground fauna (Baranová et al., 2014; Kajzer-Bonk et al., 2016; Skórka et al., 2010) and belowground fauna (Čerevková et al., 2020; Scharfy et al., 2010). It substantially alters the soil properties (e.g., soil acidity, soil moisture; Baranová et al., 2014; Sterzyńska et al., 2017), nutrient-use efficiency, and biomass production (Vanderhoeven et al., 2006), which ultimately affect the living soil communities. The socioeconomic impact of the species was also recorded. *S. gigantea* is an alternative host of insects that can be vectors of crop plant pathogens (CABI, 2020). Moreover, because the flowers of this species are bright yellow, its mass invasion decreases the landscape value (Szymura et al., 2016). It should also be noted that until recently, the species has usually been regarded as beneficial for beekeeping (Lenda et al., 2021). Although it has been demonstrated that the spread of *S. gigantea* in fact negatively affects honey production, misinformed beekeepers still favour this invasive alien species and intentionally plant it (Lenda et al., 2021).

Because there are no tested biocontrol agents of *S. gigantea*, the only available environmentally friendly methods of species control that can be used in protected areas are frequent and long-term mowing, mulching and/or grazing (CABI, 2020; Nagy et al., 2020; Szépligeti et al., 2018; Szymura et al., 2016), which reduces the density and vitality of shoots. Although soil herbicides may be effective against *S. gigantea* seedlings, the use of herbicides in PAs may not be possible because of the protection rigor. In the present study, we demonstrate how to reduce the performance of *S. gigantea* using a new method: stem breaking. The method includes a combination of mechanical (to reduce plant performance) and biological aspects (to enhance enemy attack) and may contribute to reducing invasive alien species. The method can be used in both large and small invaded patches and can even be applied in strictly protected areas. To date, the method has not been applied in other PAs or against other IAS species. However, we believe that it can also be effective in controlling other invasive alien *Solidago* species that form dense monospecific patches in PAs, including *S. canadensis or S. altissima*.

2. Materials and methods

2.1. Study area

Stem breaking tests were carried out in the Skawina meadows area (Natura 2000 site; General Directorate for Environmental Protection, 2019), which is located near Cracow in southern Poland. The site is located near the Tyniec forests, and 96% belongs to the Bielańsko-Tyniecki Landscape Park. The area is mainly covered in meadows, scrubs (82%) and deciduous forest (14%), and it includes two types of habitats: "*Molinia* meadows on calcareous, peaty or clayey-silt-laden soils" (*Molinion caeruleae*; code: 6410; cover: 1.76 ha) and "lowland hay meadows" (*Alopecurus pratensis*, *Sanguisorba officinalis*; code: 6510; cover: 4.41 ha). In this area, four butterfly species are protected under the Habitats Directive (*Lycaena dispar*, *Lycaena helle*, *Phengaris nausithous* and *Phengaris teleius*; European Commission, 1992); two bird species are protected under the Birds Directive (*Crex crex* and *Lanius collurio*; European Commission, 2009); and other rare species also occur, including butterflies (*Apatura iris*, *Brenthis ino*, *Celastrina argiolus*, *Cupido minimus*, *Lycaena tityrus*, *Maculinea alcon*, *Minois dryas*, *Nymphalis antiopa* and *Papilio machaon*) and plants (*Dactylorhiza majalis*, *Dianthus superbus*, *Epipactis palustris*, *Gentiana pneumonanthe* and *Iris sibirica*; Woyciechowski et al., 2009). All of these species co-occur with the invasive alien *S. gigantea* (Appendices: Fig. A).

2.2. General design

The northernmost part of the meadow area was included in the study (geographical coordinates: 49.998897 N, 19.841925 E) because patches of *S. gigantea* occurred only in this part of the site (cover: ~0.6 ha; Appendices: Fig. B). The source of the species invasion was a meadow neighbouring this part of the site. The individuals of *S. gigantea* were surveyed in two study years, 2012 and 2013. In total, the experiment took 40 days (20 per year). Each year, the tests were conducted between 30 June and 19 September, with 5 series of tests per year (10 series in total; Appendices: Table A). Each series was performed over 4 experimental days, which were combined within one-week intervals (Appendices: Table A). There was an 11-day break between the series (Appendices: Table A), except for 3 cases in which the break was different due to adverse weather. In total, 10 different *Solidago* patches (5 per year) were included in the study. On the first day of each series of the experiments, a new *Solidago* plot was selected at the edge of an extensive patch along a transect from west to east. Each subsequent plot was at least 10 m away from the previous plot. In total, ten different *Solidago* plots were used. The plots were squares of approximately 3 m^2. A total of 60 individual plants with comparable height were tested in each plot. Each plot was divided into two halves of equal size (1.5 m^2 area and 30 individuals) bordering each other. Using a coin-toss, one part was established as the control and the other was established as the experimental subplot.

2.3. Stem breaking and assessment of pest pressure

The initial pest assessment was carried out to determine whether the pest load was equal between the control and experimental plants. All invertebrates recorded from each control and broken plant (stem, leaves and inflorescences) were photographed without capture. Subsequently, all plants in the experimental subplot were broken by hand in the middle of the stem (Appendices: Fig. C), while the plants in the control subplot were left untouched. On the second, fourth and seventh days after breaking, pest load assessments on both the control and broken plants were repeated (Appendices: Table A). On the broken plants, the assessment included the plant parts under and above the breaking point. The procedure was repeated in a total of 10 series, and a new *Solidago* plot was used in each series. Pest assessments were always carried out between 09:00 and 17:00 by the same researcher. Moreover, 4 parameters of weather conditions were recorded: sun radiation (scale 1–3), temperature (scale 1–3), wind (scale 1–3) and cloud cover (cloudy or sunny) and included in the statistical analysis.

On the 11th day after completing each series of pest load assessments, performance assessments of the tested plants were carried out. The overall condition of the broken plants was taken into account, and the plants were classified as (1) healthy and capable of reproduction or (2) withered and incapable of reproduction.

2.4. Harmfulness scale

The number of pests among all recorded invertebrates was estimated using the invertebrate harmfulness scale (Appendices: Table B), which was developed using literature data on the negative impact of invertebrates on herbaceous plants (Najberek et al., 2016). The index H_i assigns impact values to taxonomic groups (species, genera, families) on a scale from 0 to 1, with three intermediate values (0.25, 0.5, and 0.75); $H_i = 0$: taxa exerting little or no harm to the studied plants; $H_i = 0.25$: taxa that rarely feed on herbaceous plant tissues; $H_i = 0.5$: taxa that use herbaceous plant tissues as a permanent but not the predominant food source; $H_i = 0.75$: taxa in which most species are obligatory phytophages, parasites, and pathogen carriers but a considerable share of species exert little or no harm to the studied plants; and $H_i = 1$: taxa in which all species are obligatory phytophages. The harmful H_i values assigned to each taxon (Appendices: Table B) were multiplied by the number of individuals within that taxon recorded on each plant, which provided a proxy for the number of pests attacking a given plant (N pests = N records * H_i).

2.5. Statistical analysis

The data were analysed with the use of a generalized linear mixed model (GLMM) in SPSS software (IBM Corp, 2016). The model assumed a Poisson distribution of the target variable. Pairwise contrasts were applied for comparisons between the control and broken plants. Adjusting for multiple comparisons was carried out using Fisher's least significant difference (LSD) method. The adjusted significance level was 0.05.

In the base model, the target variable was the number of recorded pests ('N pests') estimated using an invertebrate harmfulness scale. The number of pests was rounded to convert decimal values to integers, except for values of 0.25 and 0.5, which were always rounded to 1 so that no records of pests were excluded. Fixed effects were control or broken plants ('Control/Broken'), study year ('Year'), experiment day ('Experiment day') and the variable representing weather conditions ('Weather'). The last variable was obtained from a principal component analysis (PCA) of four weather factors assessed during the surveys: (1) sun radiation, (2) temperature, (3) wind speed and (4) cloudy. In the PCA, the Kaiser-Meyer-Olkin measure of sampling adequacy was 0.74, with a p-value according to Bartlett's test of < 0.001. The percentages of variance accounting for the four obtained components were 64.2%, 23.9%, 7.6% and 4.3%. The first component explained most of the variance (with an eigenvalue of 2.57 and respective component matrix of 0.93, 0.89, −0,27 and −0.91), and it was added to the model as the 'Weather' variable. Moreover, the following interactions between the variables were included in the model: 'Control/Broken * Year' and 'Control/Broken * Experiment day'. Because the number of individuals attacked by pests differed between the control and broken groups, the number of plants with pests ('N plants with pests') was included in the model as a random factor. The base model was used to generate the best-fit model (Appendices: Table C) using the lowest corrected Akaike information criterion (AICc) (Burnham and Anderson, 2002).

3. Results

In total, 844 invertebrates were recorded on the control and experimentally broken plants (379 in 2012 and 465 in 2013), among which 304 (36%) were pests (157 in 2012, 147 in 2013; Appendices: Table B). Overall, the dominant group of pests was Stylommatophora snails (N = 172; 56.6% of all pests and 20.4% of all invertebrates), and they dominated in each study year (Appendices: Table B). The dominance of this group was recorded on both the control and broken plants; moreover, it should also be noted that they were recorded more frequently in August and September than in July (Appendices: Table A). The second dominant group of pests was hoppers Auchenorrhyncha (N = 43; 14.1% of all pests and 5.1% of all invertebrates). The snails and hoppers were recorded in each study year; however, the hoppers dominated more often on control plants than on broken plants (Appendices: Table A). Usually, they were recorded on *S. gigantea* earlier than snails in July (Appendices: Table A). Interestingly, at the onset of the experiment (between 30 June and 18 July 2012), Tetranychidae spider mites were abundant (Appendices: Table A); however, in subsequent controls, these

Table 1
Results of the GLMM model for the number of pests recorded on control and broken individuals of invasive alien *Solidago gigantea* over seven experimental days.

Effect	F	df	p
Control/Broken	4.19	74	0.04
Control/Broken * Experiment day	0.82	79	0.56

pests were not recorded at all.

Overall, breaking the stem significantly increased the number of recorded pests ($p = 0.04$; Table 1, Fig. 1). Moreover, significant differences in pest load were detected between the 4 subsequent experimental days (Fig. 2). Before stem breaking (the first experiment day), there were no differences between control and experimental broken plants in terms of the recorded pests ($p = 0.72$; Table 2, Fig. 2). On the second day, the increase in pest attack on the broken plants was particularly evident ($p = 0.03$; Table 2, Fig. 2); a similar tendency was also noted on the fourth day ($p = 0.15$; Table 2, Fig. 2). On the seventh day, the level of pests recorded from the control and broken plants became similar again ($p = 0.44$; Table 2, Fig. 2).

After breaking, the performance of all experimental plants sharply decreased, with withering of the upper broken parts. Because stem breaking was applied only in 10 small plots of a large *Solidago* patch, the treatment effects did not suppress the overall invasion of the species in this area. Currently, the cover of *S. gigantea* in the study area is ~2.4 ha (Appendices: Fig. B).

4. Discussion

Biological invasions of alien species are one of the primary global threats to biodiversity in protected areas (Foxcroft et al., 2013; Gavin et al., 2018). Therefore, developing alternative, noninvasive methods of alien species control is particularly important for reducing their negative impact on native biodiversity, particularly on rare and endangered species. Nevertheless, the control of alien species in PAs is complicated, particularly in areas under strict protection, in which only environmentally friendly methods are acceptable.

We tested a potential noninvasive control method against *S. gigantea*, which is a highly invasive alien species in Europe (CABI, 2020; Lenda et al., 2021; Scharfy et al., 2010) at a Natura 2000 site. We found that hand stem breaking may reduce the generative reproduction potential of *S. gigantea* by preventing seed production by the withered upper plant part. Because the tests were applied only in 10 small plots selected in a heavily invaded area, the treatment did not stop the invasion of *S. gigantea*. Since then, the cover of *S. gigantea* in the study area has been approximately 4 times higher. However, it should be stressed that the aim of the study was to test whether the method has any chance to be effective against alien *Solidago*; consequently, we are aware that its effectiveness at a larger scale needs to be tested in the future. It should also be noted that the source of the *S. gigantea* invasion in the Skawina meadows area, which is a meadow neighbouring the northernmost part of the site, was largely destroyed in 2020 by construction works. This opportunity should therefore encourage the implementation of active control of the species, including the application of stem breaking.

We demonstrated that the treatment significantly increased the level of pest attack. Importantly, the dominant recorded pests were Stylommatophora and Auchenorrhyncha, which are both classified as generalist obligatory phytophages of vascular plants; moreover, the latter group transmits harmful plant pathogens that decrease plant performance (e.g., Bogdanowicz et al., 2008, 2007). Notably, Stylommatophora were the dominant pests of *S. gigantea* (with frequently recorded browsings) in the lowland Rów Skawiński (this mesoregion also includes the Skawina meadows area) and the montane Rów Podtatrzański (Najberek et al., 2020a, 2020b; see also Najberek et al., 2016). Stylommatophora were indicated as effective pests against invasive alien species that are becoming established in new areas (Najberek et al., 2020a, 2020b).

The application of stem breaking does not require virtually any equipment and can be performed by non-qualified volunteers. Thus, it is economic, efficient and ready-to use in most situations in which control measures are considered. An additional advantage is that in practice, its application does not affect any neighbouring areas in terms of emission of chemicals, noise or physical disturbance, which may be crucial in strictly protected areas. However, if the protection regime allows it, stem breaking can be ad hoc modified and

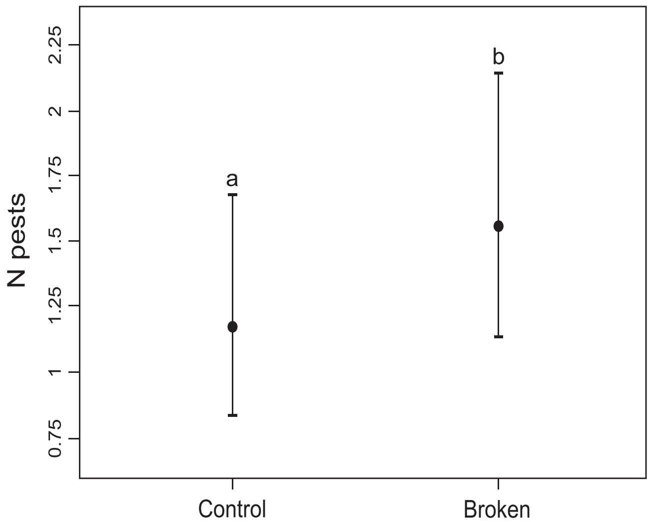

Fig. 1. Estimated mean number of pests ('N pests') recorded on the control and broken individuals of invasive alien *Solidago gigantea* (± confidence intervals). Letters above T-bars indicate significant differences in pest load between the control and broken individuals.

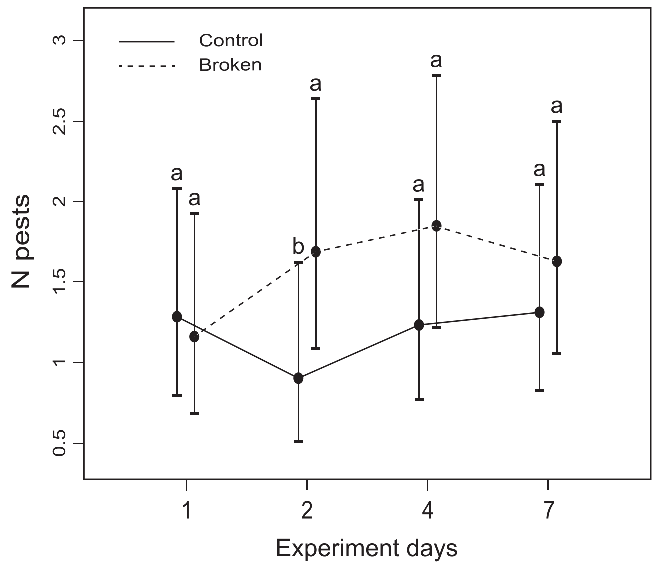

Fig. 2. Estimated mean number of recorded pests ('N pests') on the control and broken individuals of invasive alien *Solidago gigantea* (± confidence intervals) on subsequent experiment days. Letters above T-bars indicate significant differences between the control and broken individuals on particular days.

Table 2
Results of pairwise contrasts for the interaction between the variables 'Control/Broken' and 'Experiment day'. The interaction was generated in the GLMM model for the number of pests recorded from invasive alien *Solidago gigantea* (see Table 1).

Experiment day	SE	t	df	p
1	0.35	0.36	73	0.72
2	0.35	-2.21	73	0.03
4	0.41	-1.46	73	0.15
7	0.40	-0.78	73	0.44

applied in a variety of ways, including using all-terrain motor vehicles or plough animals, to pull any piece of equipment capable of breaking stems of plants. However, it should be stressed that we did not test the mechanical treatment variant; thus, using motor vehicles or plough animals in stem breaking should be considered with due caution.

It should also be noted that the abundance and richness of insects (including pests) increase with vegetation cover (Jaganmohan et al., 2013; Salman and Blaustein, 2018), which is associated with temperature fluctuations in areas where vegetation cover is reduced (Barton and Ives, 2014; Chen et al., 2009; Ju et al., 2015). It should be stressed that broken plants also form a cover that protects insects against excessive solar radiation. However, we observed that the broken plants provided only temporal protection because their upper broken parts always progressively turned dry and then shrank. Although this process inevitably led to an increase in mean temperature, this increase was gradual. This gradual change in temperature represents another advantage of alien plant control by stem breaking over regular mowing, which drastically changes the thermal regime and may have a very negative effect on insects (Ju et al., 2015).

Another advantage of the proposed method relative to classical biological control is that the most effective biocontrol agents do not need to be identified and rigorous tests are not required because all enemies locally present in the area in question may be involved, including harmful invertebrates, fungi, bacteria and viruses.

Stem breaking should be most effective in dense and monospecific patches, such as those formed by invasive alien *S. gigantea*. We suggest that breaking is carried out twice per vegetative season. The first treatment should be applied when the plants are adults and their stems are more lignified and prone to breaking. However, it should also be applied before the flowering phase, which guarantees the prevention of seed production by broken (and subsequently withered) individuals. Although it cannot be excluded that broken individuals with inflorescences are still able to produce viable seeds before they wither, *S. gigantea* spreads mainly by rhizomes at invaded sites (Weber and Jakobs, 2005); therefore, limiting seed production will curb the expansion of this species into adjacent localities. In Central Europe, including Poland, the first treatment could be carried out in July, when Auchenorrhyncha attacks on broken plants are most frequent. The second treatment is also required and should be applied to eliminate individuals who germinate very late in the season (Gioria et al., 2016; Najberek et al., 2020a, 2020b), thus avoiding the first treatment. The second treatment should be carried out in early August, when Stylommatophora intensively feed on giant goldenrod leaves. Moreover, because the inflorescences will already be developed during the second treatment, this treatment should be applied before the seeds are mature and ready to be dispersed.

In addition, it should be noted that in the stem breaking tests, invertebrates were photographed without capture. Compared with the capturing method, the proposed method allows for the inclusion of legally protected invertebrates, which is particularly relevant in PAs. Moreover, such a procedure does not affect the level of enemy pressure during subsequent surveys because their disturbance is kept to a minimum (Najberek et al., 2020a, 2020b).

We estimated the numbers of pests among all recorded invertebrates using the invertebrate harmfulness scale (Najberek et al., 2016). The advantage of this approach is that traditional assessments of the negative impact of pests on plants require the time-consuming identification of large numbers of invertebrates at the species level by a team of experts specializing in different taxa (Najberek et al., 2017a, 2017b, 2020a, 2020b), and it often involves killing the collected invertebrates, which may bias the results of subsequent surveys at the same site. Furthermore, collection may be restricted or even not possible for protected species and in protected areas, such as Natura 2000 sites. The harmfulness scale allows an efficient assessment of the negative impact of pests without the need to collect and kill individuals because pictures taken in the field are sufficient for assigning them to a higher taxonomic level.

A factor that could have obscured the obtained results is that rhizomes of the surveyed stems were not taken into consideration in the tests. *S. gigantea* is a perennial herb that produces long (up to 90 cm in length) and highly branched rhizomes at 10–20 cm deep in the soil, with 3–50 rhizomes per ramet produced, and the root system varies in size and density (Weber and Jakobs, 2005). Thus, it cannot be estimated how many of the surveyed stems came from the same root system. Moreover, it cannot be excluded that different plots were joined by the same roots because the plots were occasionally separated by only several metres. It should also be noted that a cover in which broken plants form after stem breaking can prevent the penetration of seeds of native species in the area. In further tests of the method, these cons of stem breaking should be included in the study design and carefully assessed.

In conclusion, considering the simplicity and versatility of the proposed method, stem breaking has the potential for use against the invasive alien *S. gigantea*, particularly in ecologically sensitive and strictly protected areas. However, it should be stressed that the tests of the method presented here were carried out using only small plots of the species and stem breaking was only performed by hand. Therefore, further tests are needed to assess the effectiveness of the method against *S. gigantea* at a larger scale. Such further work will also allow for an analysis of the real costs of the method and tests of its possible positive or negative influence on organisms that co-occur with alien *Solidago* in invaded areas.

CRediT authorship contribution statement

Kamil Najberek: Original research idea, Study design, Field surveys, Statistical analyzes, Writing – original draft, Writing – review & editing, Funding acquisition. **Wojciech Solarz:** Study design, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Institute of Nature Conservation, Polish Academy of Sciences (Cracow, Poland), through grant funding for PhD students.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01785.

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