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Distribution, Ecology and Invasion Potential of *Sorghum halepense* (Poaceae) in the Insubric Region (Northern Italy and Southern Switzerland)

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ABSTRACT: *Sorghum halepense* (L.) Pers. (Johnson grass, Poaceae) is a worldwide problematic alien species, rapidly expanding its alien range in Europe. This study reconstructed the spread history, and assessed the current distribution, ecological traits, and invasion potential of this species in the Insubric region of northern Italy and southern Switzerland. Herbarium and occurrence data showed that its spread began in the late 19th century and has accelerated recently in the foothill zone, progressing northward and upward. High-cover populations occurred in anthropogenic habitats, especially ruderal and agricultural areas. Morphological analyses revealed statistically significant site-dependent differences in plant height (140–292 cm) and specific leaf area (12.32–1077.59 cm²/g⁻¹). CCA analysis linked species occurrence to lower levels of soil phosphorus and calcium. The species shows medium-high invasive potential in the Insubric region due to the combination of high reproductive (sexual and vegetative) and spread potential, combined with medium impact potential on native biodiversity (competition, allelopathy) and medium-high impact on agriculture (severe crop losses and pathogen host). According to impact classification schemes, *S. halepense* falls under ‘Moderate’ (environmental) and ‘Major’ (socioeconomic) impact categories. Because *S. halepense* can develop herbicide resistance, other control measures should be preferred. Ongoing climate warming and land use changes are expected to further facilitate its spread across and beyond the Alps.

KEYWORDS: Canton Ticino; EICAT; impact; introduction; invasive species; Johnson grass; herbarium specimen

1 Introduction

Within the southern slope of the Alps, the Insubric region spans over northern Italy (Lombardy and Piedmont) and southern Switzerland (Canton Ticino) and is characterised by a particularly mild and wet climate [1,2] which supports remarkable native plant diversity and facilitates the establishment of alien species in the lowlands [3,4]. Over the last few decades, several new alien plant species have been identified (e.g., [5–7]), and already established ones have considerably expanded their range throughout the region [8,9]. *Sorghum halepense* (L.) Pers. (Poaceae), Johnson grass, is a notable example of the latter case. It is a plant well adapted to a humid subtropical climate [10]. Indeed, its recent rapid spread in the Insubric region has caused concern among the competent authorities, especially in the Swiss part of the region. This species is considered invasive in an increasing number of countries worldwide [10], causing significant economic losses in agricultural systems [11]. Therefore, a deeper understanding of the species’

distribution, ecology, and invasion potential is crucial for effective management policies. This is especially true in the Insubric region, where the species is in the early phases of invasion.

Sorghum halepense is a perennial C4 rhizomatous geophytic grass that can reach over 2 m in height. The most characteristic traits are the presence of a wide panicle, long and narrow leaves with a prominent white midrib, and relatively large creeping rhizomes [12]. Despite its uncertain origin, *S. halepense* is considered native to the area spanning from northeast Africa to the Indian subcontinent [13] and, according to POWO [14], actually across all northern Africa to Mainland Southeast Asia. Several biological features, such as rapid growth, secretion of allelopathic substances, and efficient vegetative and sexual reproduction have contributed to the successful establishment of this grass throughout the world outside its native area over the last two centuries, after being spread mainly as a forage plant or through contaminated seed stock and soil (e.g., [11,15]). Indeed, it currently occurs on all continents except Antarctica [11,14] but prefers subtropical and warm temperate climates [15,16]. In Europe, *S. halepense* has been recorded for over five centuries in some southern and warmer regions, such as in Italy [17,18], but has been spreading northward since the end of the 1800s [10,11,19]. In the last three decades, the species has invaded new areas in Central Europe (e.g., in Austria, Hungary, Slovakia and Slovenia [19–23]) and occupied new types of habitats by apparently expanding its ecological niche, probably promoted by climate change, monoculture crops and the misuse of herbicides [11,23–25].

For instance, *S. halepense* is currently considered a threat to agriculture in over 50 countries [11], considerably damaging the world's main crop production and causing huge economic losses [19,23,26–29]. Only recently, some authors have pointed out that *S. halepense* can reduce the biodiversity of native species in the United States [30], mainly through size-asymmetric competition [31], and may thus pose a threat to natural systems, especially grasslands [29]. In Europe, the species has not yet been thoroughly investigated, and the few relevant studies available (e.g., [11,19,22,23]) primarily focused on agriculture impacts and control methods. Although *S. halepense* is not on the EU's list of invasive alien species of union concern [32] nor on any lists by the European and Mediterranean Plant Protection Organization [33], it is increasingly recognized as a problem at the national level. Indeed, it has been included in Switzerland's List of potentially invasive species [34] and on the Black Lists of some northern regions of Italy, such as Piedmont ([35]; not in Lombardy, see [36]), and Portugal as well (see law decree 92/2019 of the Portugal republic on Invasive Aliens). In the remaining European countries, where it is present, it is mainly treated as an agricultural weed rather than a regulated invasive species.

The current spread of *S. halepense* in Central Europe and predictions about its future distribution (e.g., [24]) explain concerns about the species in the Insubric region, where climatic conditions appear to be increasingly favourable for the species and no scientific research has been published yet. Therefore, in this study, we aimed at: (1) reconstructing the invasion history and current distribution of *S. halepense* based on herbarium specimens, databases, literature, and occurrence records, (2) investigating aspects of its ecology, in particular its growth ability, in the main habitats that it occupies; and, finally, (3) assessing and discussing its invasion potential in the Insubric region, especially in natural and semi-natural habitats. Our goal was to provide information on *S. halepense* outside croplands to eventually support national risk assessments and subsequent listings and decisions on regulation, control and management of the species.

2 Methods

2.1 Distributional Analysis

The present study focuses on the Insubric region (see Supplementary Material S1), i.e., the region that connects the southern Central Alps with the Po Valley and is characterised by a sequence of mountain chains, several glacial Prealpine lakes, moraine hills, and plains (Fig. 1a) and the so-called 'Insubric climate' [1,2].

The historical distribution of *S. halepense* was investigated using information associated with herbarium specimens (both general and historical collections) from Northern Italian and Swiss herbaria and literature data either published or retrieved from web sources (Supplementary Material S2) (e.g., [12,37–42]). Only herbarium specimens collected in Switzerland, Lombardy and Piedmont were considered, excluding those lacking useful information, duplicate specimens, and specimens collected in the same year at the same place. If not available and whenever possible, the site and/or the year of collection was inferred based on reliable information in the literature about the operational area of the collectors or their personal herbarium collections to which the sample belongs, and by comparison with data from surrounding areas. Datasets were organized (by collection year, collection site, collector, herbarium, and any additional information), georeferenced with Google Earth Pro (v.7.3.4, 2023; <https://www.google.com/earth/about/versions/#earth-pro>), and then mapped with QGIS software (v.3.22.3 'Białowieża', 2022; <https://qgis.org>) using base maps from OpenStreetMap (© OpenStreetMap contributors, 2022) licensed under the Open Data Commons Open Database License (ODbL) and the Creative Commons Attribution-ShareAlike 2.0 License (see www.openstreetmap.org/copyright for details). To graphically visualize the spread dynamics of *S. halepense* and compare the distribution data over time, records were classified into five temporal categories based on consecutive periods in which 20% of herbarium specimens were collected (following the methods by Ciappetta et al. [43] for *Ambrosia artemisiifolia*). Finally, to infer the collection rate and discuss specimen collections in the context of *S. halepense* spread, the cumulative number of specimens collected over the years was plotted on a graph using MS Excel.

The current geographical distribution of *S. halepense* in the Insubric region was reconstructed using occurrence records from Canton Ticino, Lombardy, and Piedmont, from a wide range of sources, including national and regional floristic databases, field work during this study, herbaria, natural history museums, universities, and local experts (see full list and data extraction criteria in Supplementary Material S3). The full dataset from the three regions was then mapped using QGIS (v.3.40.5-Bratislava, 2025; <https://qgis.org>).

2.2 Ecological Analysis

The ecological analysis of *S. halepense* focused on Canton Ticino, the north-western part of the Insubric region. To select appropriate sites, habitats in which the species grows were preliminarily selected by superposing the georeferenced occurrences on a background map of aerial photos and activating a layer of the map of natural environments available on the Swiss online geographic mapping service Swisstopo (<https://map.geo.admin.ch/>). Subsequently, field surveys allowed selection of four types of habitats occupied by *S. halepense* from the lowlands to the hill/mountain area: (1) hygrophilous habitats (canal banks and lakeshores), (2) cultivated areas, (3) meadows/roadsides, (4) meadows (less representative type of habitat, only present in the hill/mountain area). Finally, three sampling sites were chosen for each lowland habitat type, whereas only one was found in the meadows in the hill/mountain area. Nine sites were located in Canton Ticino, as far as possible from each other, and one was in Italy at the southern limit of the Insubric region (Pozzuolo Martesana; see Supplementary Material S4).

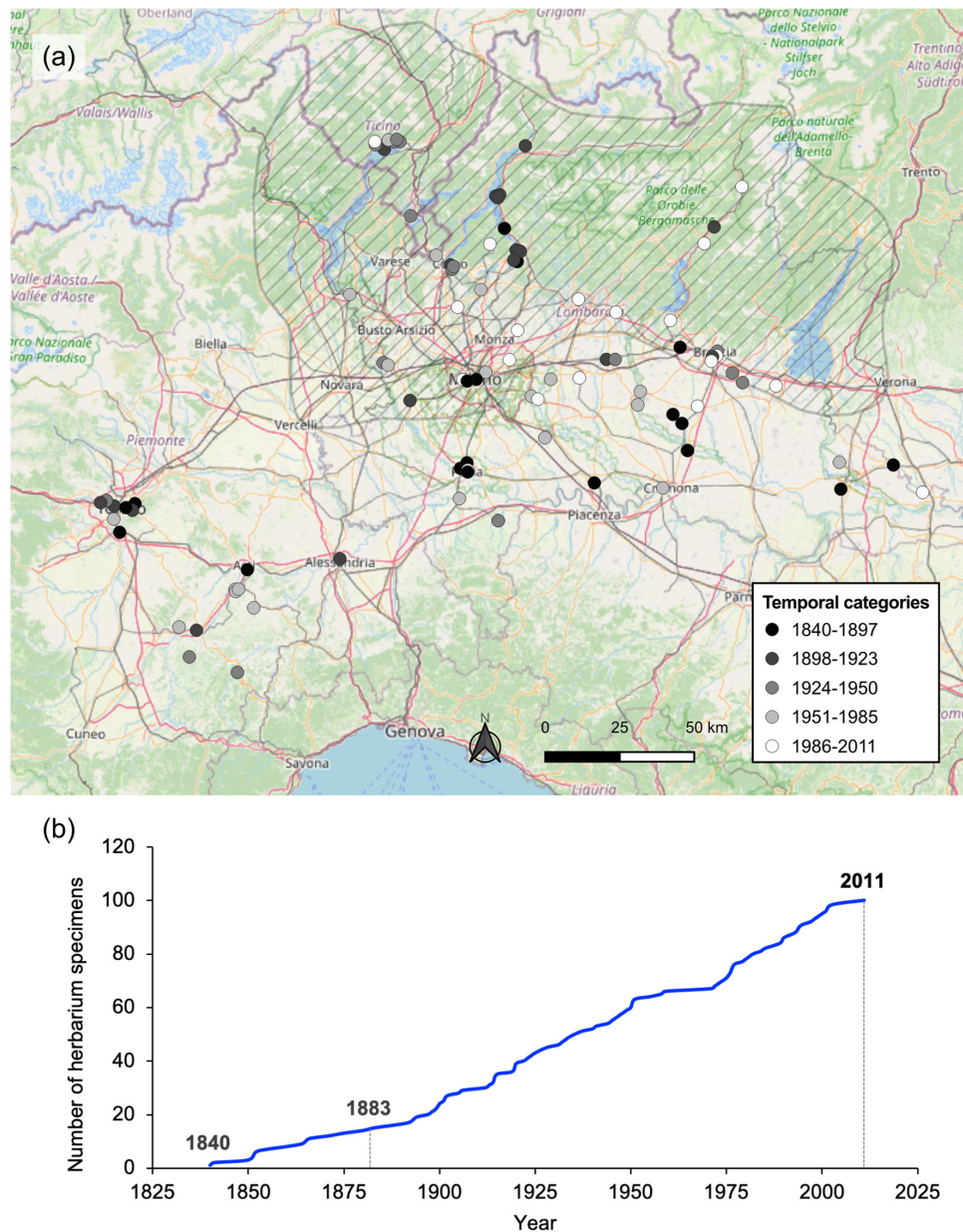


Figure 1: Distributional analysis of *Sorghum halepense* using herbarium data. (a) Spatial distribution of *S. halepense* herbarium specimens in Canton Ticino, Piedmont, and Lombardy, classified into five temporal categories based on years in which 20% of the specimens were collected, following the method of Ciappetta et al. [43]. Darker dots represent older specimens. The boundaries of the Insubric region (shaded area) are indicative (see Supplementary Material S1). (b) Cumulative number of *S. halepense* herbarium specimens collected in Canton Ticino, Lombardy, and Piedmont from 1840 to 2011 (year of the most recent specimen). The first specimen from the Insubric region was collected in 1883.

Vegetation surveys were performed in 44 plots (each 5×5 m). At each site, five plots were randomly selected, except for two sites (Pianezzo and Tenero), where only one and three plots, respectively, could be selected because of very small habitat patches. In each plot, the vegetation survey consisted of a list of vascular plant species and a visual estimate of the cover (total and single species). Species were determined

using identification keys of floras [12,40,44] and digital identification tools [40]. Precise coordinates and elevation were recorded for each plot using FlorApp, and the species list was compiled using the 'vegetation survey module'.

For the morphological trait and soil analyses, in each sampling plot, ten *S. halepense* specimens and an average of two soil samples were collected. Plant height (cm), spike length (cm) and major leaf length (cm) were measured directly in the field after collection. Leaf area (cm²) was calculated for the second leaf under the spike with Easy Leaf Area Free application [45]. Plant and leaf dry weight were measured with a digital electronic analytical scale (0.0001 g precision) after drying them in an oven at 65°C for 58 h. Finally, the specific leaf area (SLA) was calculated by dividing the leaf area by the leaf dry weight. Soil samples were prepared and analysed following the protocol described in Gentili et al. [46]. Thirteen parameters were determined: apparent texture (quantity of sand, silt, and clay), pH, carbonates (Ca), organic matter and organic carbon (C), total nitrogen (N), carbon/nitrogen ratio (CN), cation exchange capacity (CSC) and three exchangeable cations (Ca, Mg, K), base saturation rate, and assimilable phosphorus [47,48].

For statistical analyses, vegetation survey data were used to infer the mean alpha-diversity (species richness) and beta-diversity (Whittaker index) using the Past software (v.4.02; [49]), and then to analyse differences of ecological factors and morphological traits among sites. In particular, the variance of the three ecological variables (alpha-diversity, beta-diversity and *S. halepense* cover) was analysed with a one-way ANOVA and linear models (lm), whereas that of morphological traits (plant height, spike length, leaf length, dry weight, leaf area, leaf weight and SLA) used linear mixed models (lmm) and site replicates as random factor. ANOVA was performed after applying a Shapiro-Wilk normality test and was followed by a Tukey post hoc test for multiple mean comparisons, and a Bonferroni correction to strengthen the statistical evidence. When necessary, to meet normality assumption, data were log transformed. The analyses were performed using the software R [50].

To understand the relationships among plots, vegetation, and environmental variables (ecological and soil variables, plus latitude, longitude and elevation), a Canonical Correspondence Analysis (CCA) was performed using CANOCO software (v.4.5; [51]). A correlation analysis was performed to examine the Spearman index and exclude the most correlated variables (Spearman index > 0.75), namely, those that provide the same information describing in the same way the distribution of data [52]. To avoid multicollinearity among variables, variance inflation factor (VIF) was assessed through a specific function of the CANOCO software. In this way, 11 variables (elevation, latitude, species richness, Whittaker index, *S. halepense* cover, sand, pH, total N, C/N, cation exchange capacity, calcium, magnesium and phosphorus) were retained for subsequent analyses.

2.3 Assessments of Invasive Potential and Impacts

The invasive potential results from a combination of the spread potential and the negative impacts (impact potential) caused by a species (e.g., [53]). To assess the invasive potential of *S. halepense* its biological traits, spread potential, and published impacts were compared to the criteria listed in the Catalogue of criteria by InfoFlora [54], used to compile the Black List and Watch List of alien species of Switzerland [55] and, more recently, to support compilation of the new national list of invasive and potentially invasive alien plant species [32]. Criteria about the spread potential consider sexual and vegetative reproduction rate of the assessed species, persistence of a seedbank, natural and human-mediated dispersal, etc. Those about the impact potential consider impacts on human and animal health, native species, ecosystems (structure, water and nutrient cycles, etc.), infrastructure, and economy (e.g., agricultural systems, tourism, etc.). In this type of risk assessment, a percentage score representing three levels (high, medium, low) is assigned to

each criterion based on the respective information available for the assessed species. These percentages are used to support the discussion of the level (high, medium, low) of the invasive potential.

Impacts of *S. halepense* on native environment were assessed with the Environmental Impact Classification of Alien Taxa (EICAT; [56,57]) following the protocol by the International Union for Conservation of Nature [58]. An impact score is assigned using a five-category system (massive, major, moderate, minor, and minimal concern), depending on the taxonomic level that is negatively affected by the alien species (individual, species, community) and whether damages are reversible or irreversible. These five categories are also used by the Socio-Economic Impact Classification of Alien Taxa (SEICAT; [59]) to score the impact of alien species, referring to their ability to interfere with human activities and with economic wellbeing. The magnitude of the impact of *S. halepense* was scored based on EICAT/SEICAT-relevant information.

The relevant information on *S. halepense* for assessment was gathered by searching the scientific literature (Google Scholar, Scopus, WorldCat, using the species name as a keyword) and using the results of this study. Assignment of percentage scores and EICAT and SEICAT categories was performed by the first author, and results were used to support the discussion of the species' spread and impact potential and draw conclusions on its invasion potential in the Insubric region.

3 Results

3.1 Distributional Analysis

A total of 237 *S. halepense* specimens from 22 herbaria (out of a total of 33 contacted) were examined, but only 99 (about 42%) were useful for inferring the historical distribution and spread history of the species in the Insubric region in general, and in Canton Ticino, Piedmont and Lombardy more specifically (Supplementary Material S2).

The five temporal categories with each 20% of collected herbarium specimens were: 1840–1897, 1898–1922, 1923–1950, 1951–1982, and 1983–2011 (Fig. 1a). The oldest specimens (not included in the categorization due to the lack of precise collection dates) date back to the late 1700s and early 1800s and came from ruderal areas, cultivated fields, and river and canal banks in major provinces of the Po Valley (Mantua, Turin, Pavia), which are off the Insubric region considered in this study. The first specimen with a precise date (accuracy within one year) is from 1840 and was collected in the hills of Turin (Italy). Approximately a century later, the species began to be collected in more northerly localities (Lecco, Como, Canton Ticino), within the foothill area of the Insubric region, near larger urban centres and lakeshores. The first specimens from this area date back to 1883 and were collected in Galbiate (LC), Lombardy. In general, the oldest specimens from the Insubric region come mainly from major urban centres, while more recent ones also come from suburban areas and roadside meadows. The cumulative number of herbarium specimens collected over time remains nearly constant from 1840 to 1900, increases slightly until the early 2000s, and then shows a sharp decline up to 2011, when the last specimen was collected in Milan (Fig. 1b).

A total of 2914 occurrence records from Canton Ticino, Piedmont and Lombardy (Fig. 2a) were used to infer the current distribution of *S. halepense* in the Insubric region (~1400 occurrences; Fig. 2a, black dots). The species is widely distributed across the entire Po Valley, and, within the Insubric region, in anthropogenic habitats surrounding Maggiore, Lugano and Como lakes, Mesolcina Valley, as well as the lowlands of the main valleys, and the Brescian and Bergamasque Pre-Alps, throughout the Camonica Valley. In this region, it is widespread from the lowland level up to 1378 m a.s.l. (in Bergamasque Pre-Alps), with 98.2% of the occurrences below 700 m a.s.l. in the foothill zone. The northernmost occurrence is in Ponto Valentino (Acquarossa municipality, 615 m a.s.l.) in Canton Ticino. According to the information provided

on occurrences, the species most frequently colonises anthropogenic habitats, including ruderal areas, cultivated fields, roadsides, irrigation canals and ditches, and wetlands. Based on field observations of this study, the species also occurs in semi-natural areas, such as unfertilized meadows (e.g., Agra, Bellinzona along the river bank), also in sub-montane areas (e.g., above Brissago, 810 m a.s.l., where the species reaches the highest elevation in Canton Ticino; Brè sopra Lugano, 790 m a.s.l.; Mergoscia, 720 m a.s.l.), though always in proximity to infrastructures (roads or buildings). The cumulative number of occurrence records (Fig. 2b) increases gradually from the mid-1990s until 2003, followed by a sharp rise between 2004 and 2009. After a period of slower growth from 2010 to 2019, the number increased steeply again from 2020 to the present (while herbarium records end in 2011).

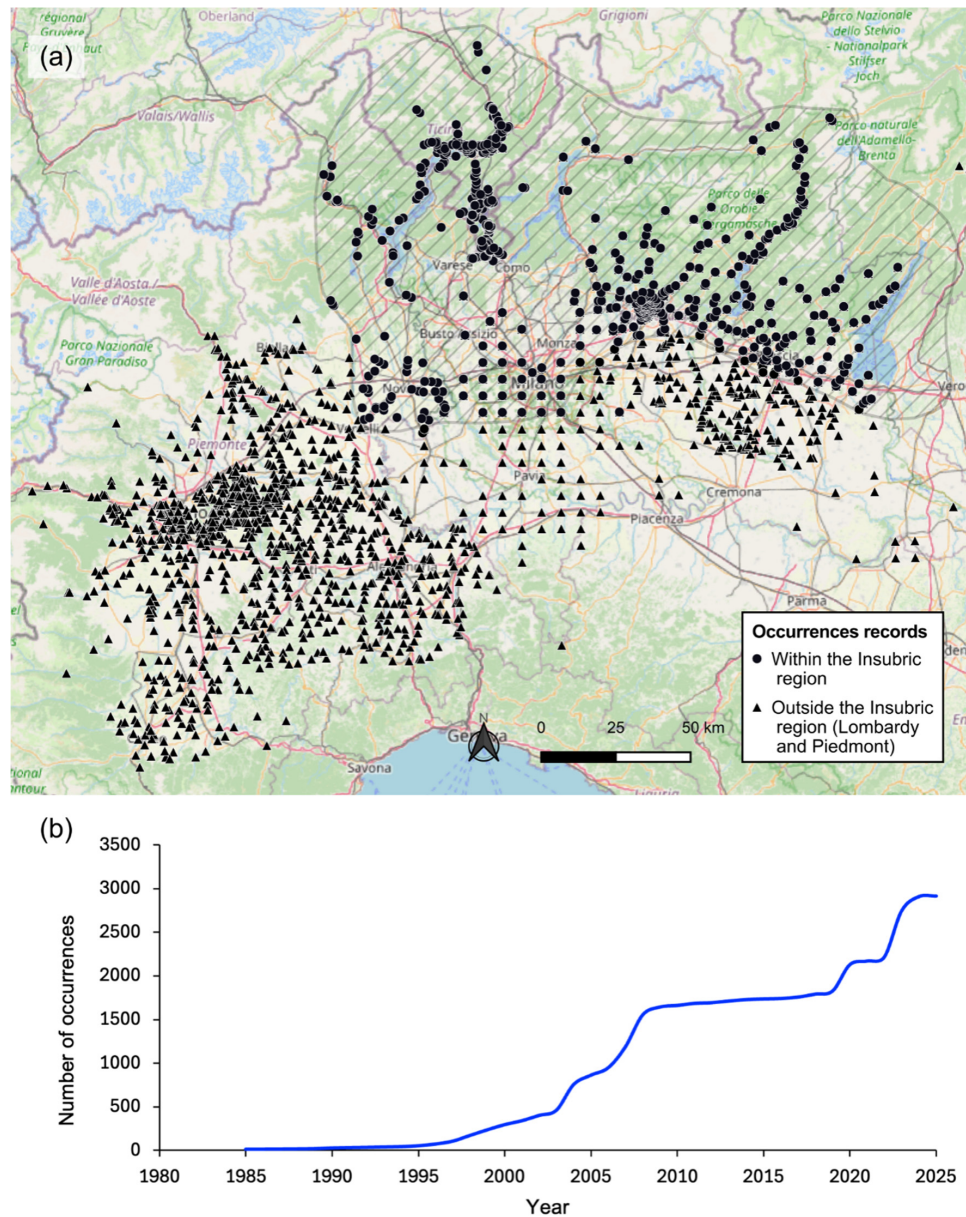


Figure 2: Distributional analysis of *Sorghum halepense* using occurrence data. (a) Spatial distribution of *S. halepense* in Canton Ticino, Lombardy and part of Piedmont based on all occurrences used in this study. (b) Cumulative number of *S. halepense* occurrences in Canton Ticino, Lombardy and part of Piedmont from 1990 to 2024.

3.2 Ecological Analysis

The three main biotic factors investigated such as alpha diversity (richness), the beta diversity (Whittaker index) and *Sorghum halepense* cover exhibited significant differences across sites. Specifically, Alpha diversity consisted of a total of 123 species identified through vegetation surveys, with 5 and 21 species in the poorest and richest plots, respectively, and a mean of 12 species per plot. Site-level differences were statistically significant (ANOVA; $F_8 = 14.883$; $p < 0.001$) (Fig. 3a). Mean species richness was lowest in Cadenazzo (6 species) and highest in Stabio (18 species). The species most frequently found in association with *S. halepense* were *Arrhenantherum elatius* (Poaceae; 23 plots, 52% of all plots), *Calystegia sepium* (Convolvulaceae; 21 plots, 48%), and *Setaria pumila* (Poaceae; 18 plots, 41%). Difference in Beta-diversity among sites was statistically significant ($F_8 = 12.941$; $p < 0.001$) (Fig. 3b); it was lowest in Balerna (Whittaker index = 0.33 mean per plot) and highest in Pozzuolo (0.59), with a mean of 0.44 per site. Differences in *Sorghum halepense* cover among sites were statistically significant ($F_8 = 2.2724$; $p < 0.05$) (Fig. 3c); it was lowest in Stabio (27% mean plot) and highest in Balerna (about 59%), with a mean cover of 47.6% per site.

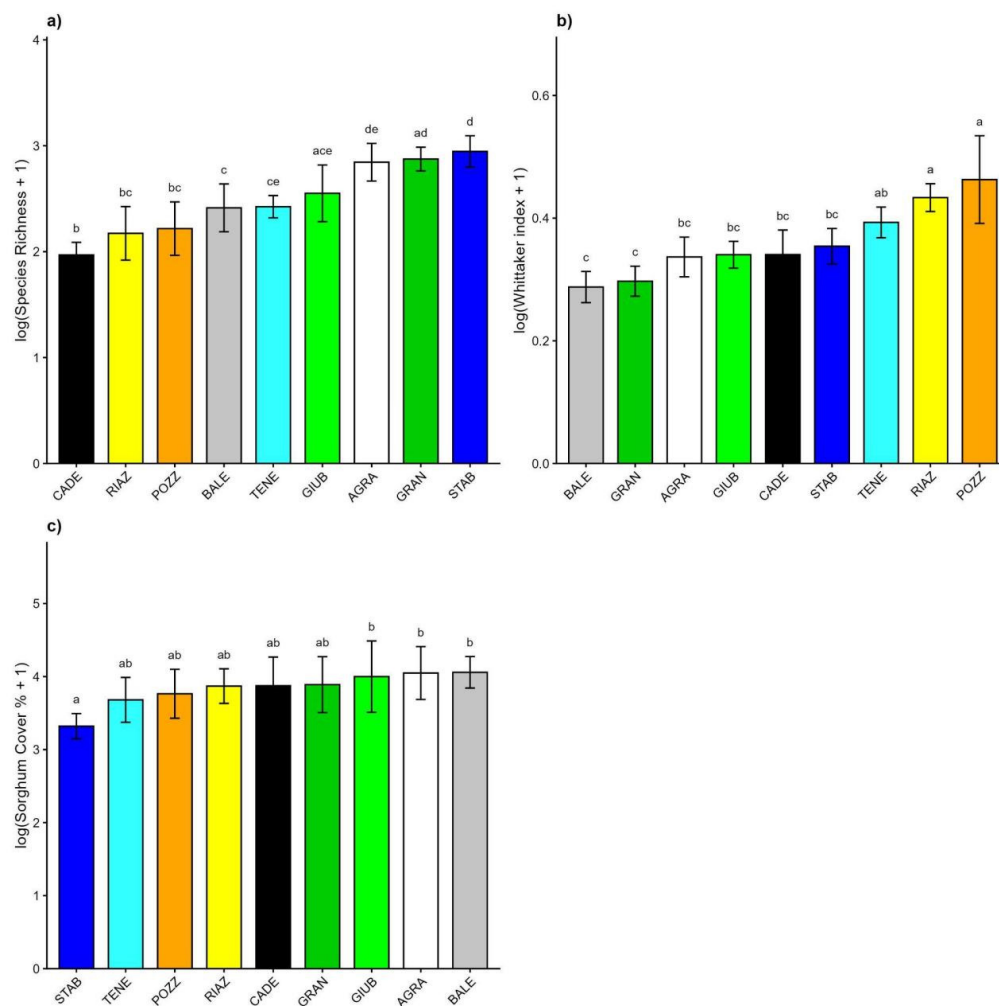


Figure 3: Bar charts showing the log of mean and standard deviation of species richness (a), Whittaker index (b) and *S. halepense* cover (c) in the surveyed sites. Different letters indicate significant differences among sites according to the *post hoc* test of Tukey ($p < 0.05$; ANOVA).

The same parameters showed no statistically significant differences among the three habitat types where the species grows: cultivated, hygrophilous and meadows s.l. (i.e., meadow + roadsides) areas (species richness: $F_{2,6} = 0.25527$; $p = 0.7827$; Whittaker index: $F_{2,6} = 0.27213$; $p = 0.7707$; *S. halepense* cover: $F_{2,6} = 1.0712$; $p = 0.4001$).

In the morphological analyses of *S. halepense*, plant height ranged from 140 to 292 cm (mean 195 ± 28) and differed statistically among sites ($F_{9,35} = 2.796$; $p < 0.05$) (Fig. 4a). Based on mean values per site, the shortest and tallest specimens were found in Agra (177 ± 19 cm) and Pozzuolo (230 ± 33 cm), respectively, based on mean values per site. Inflorescence length ranged from 13 to 65 cm (mean 28.5 ± 6.5 cm), with significant differences among sites ($F_{9,35} = 17.183$; $p < 0.0001$) (Fig. 4b); both extremes were observed in Riazzino. Based on mean values per site, the shortest inflorescences were in Agra (22 ± 2.5 cm) and the longest in Cadenazzo (38 ± 6.5 cm). Plant dry weight ranged from 3.4 to 106.63 g (mean 14.46 ± 10.53) and differed statistically among sites ($F_{9,35} = 4.0864$; $p < 0.01$) (Fig. 4c), with the lightest plants found in Agra (mean 8.85 ± 3.43 g), and the heaviest in Cadenazzo (24.42 ± 18.77 g). Leaf length ranged from 32 to 92 cm (mean 65 ± 11), with no significant differences among sites ($F_{9,35} = 1.5779$; $p = 0.1604$) (Fig. 4d). The shortest leaves were in Pianezzo (mean 56.5 ± 6 cm), and the longest in Balerna (70 ± 9.5 cm). Leaf area ranged from 2.50 to 90 cm² (mean 22.5 ± 15 cm²), and differed significantly among sites ($F_{9,35} = 3.14712$; $p < 0.01$) (Fig. 4e), with the lowest values in Agra (mean 11.58 ± 7.46 cm²) and the highest in Giubiasco (30.44 ± 13.09 cm²). Leaf dry weight ranged from 0.011 to 0.974 g (mean 0.144 ± 0.109), with no significant differences among sites ($F_{9,35} = 1.367831$; $p = 0.2398$) (Fig. 4f). The lightest leaves were found in Agra (mean 0.074 ± 0.048 g) and the heaviest in Cadenazzo (0.186 ± 0.089 g). Specific leaf area (SLA) ranged from 12.32 to 1077.59 cm² g⁻¹ (mean 164.83 ± 55.5), and differed significantly among sites ($F_{9,35} = 5.201$; $p < 0.001$) (Fig. 4g). The lowest SLA was in Balerna (mean 138.01 ± 29.18 cm² g⁻¹) and the highest in Stabio (202.59 ± 133.96 cm² g⁻¹), which also included the specimens with the lowest and highest values, respectively.

Differences in the same morphological traits among habitat types (Fig. 5a–g) were statistically significant for inflorescence length ($F_{3,41} = 5.201$, $p < 0.001$) (Fig. 5b), plant dry weight ($F_{3,41} = 4.0567$, $p < 0.05$) (Fig. 5c), leaf area ($F_{3,41} = 2.29057$, $p = 0.0925$) (Fig. 5d) and SLA ($F_{3,41} = 2.871$, $p < 0.05$) (Fig. 5e). In general, cultivated and hygrophilous habitats showed the highest values for all morphological traits, except for SLA.

For the CCA, the correlation among the 11 selected environmental variables and the distribution of surveyed species and plots is shown in Fig. 6. The four canonical axes cumulatively explained 53.7% of the total variance, with the first and second axes accounting for 30.6%. Species and plots mostly clustered in the first and third quadrants and were significantly distributed along the first and second axes (Table 1). The environmental variables that best explained variance ($p < 0.001$) were: assimilable phosphorus ($\lambda = 0.39$), elevation ($\lambda = 0.32$), species richness, calcium, and longitude (Table 2). All sites except Stabio and some plots of Tenero were negatively correlated with the phosphorus and calcium gradients. The altitudinal gradient was negatively correlated with Pozzuolo, Grancia, and Giubiasco, while pH showed a positive correlation with these same sites and a negative one with Agra, Balerna, and Tenero. Regarding habitat types, all hygrophilous sites fell in the first quadrant, negatively correlated with phosphorus, calcium, and elevation gradients, and positively with the Whittaker index and pH. Meadows/roadsides and cultivated sites (except for the Stabio, positioned on the opposite side) were arranged between the graph centre and the fourth quadrant, negatively correlated with phosphorus, calcium, pH, and Whittaker index, and positively with the altitudinal gradient.

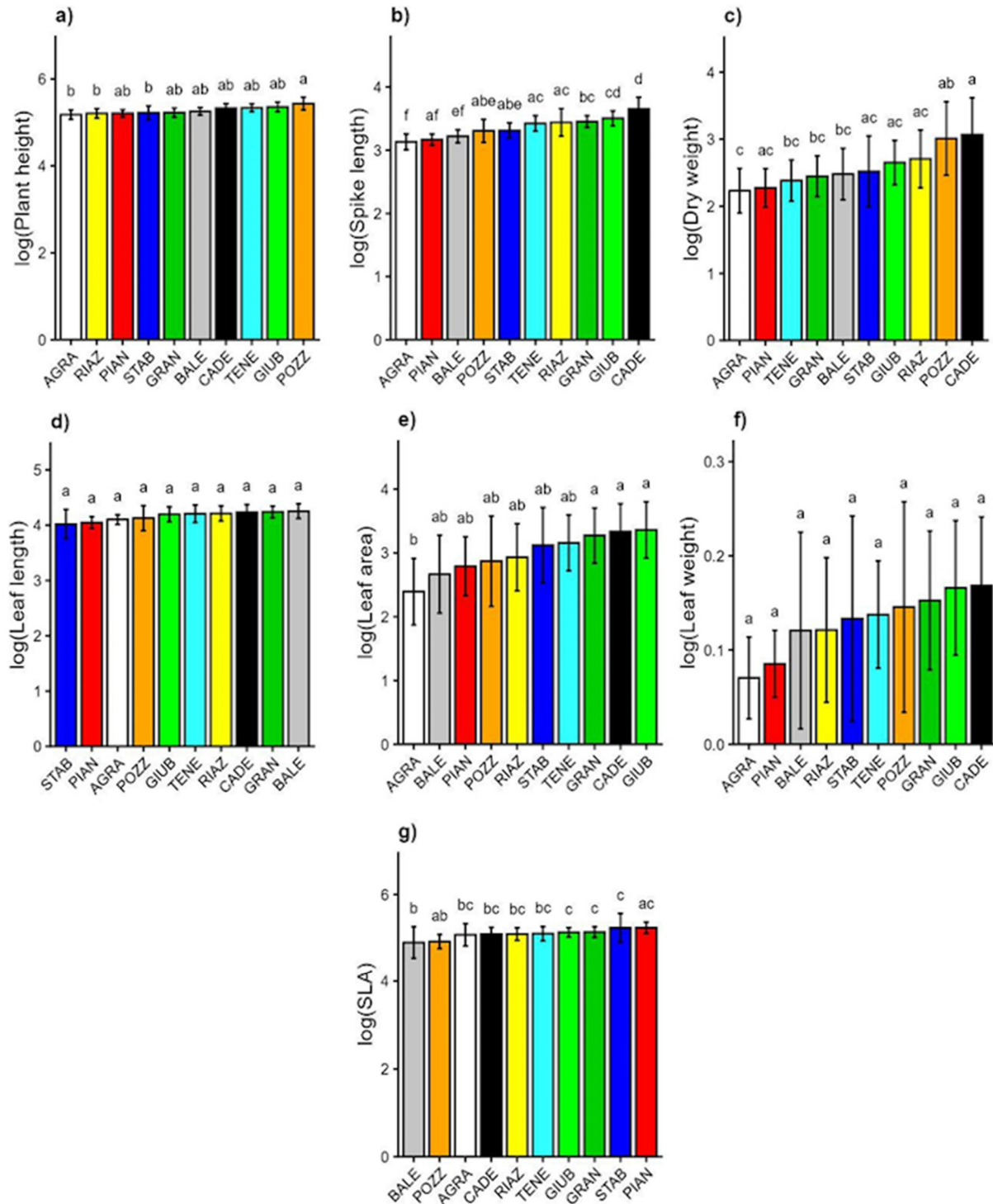


Figure 4: Bar charts showing the log of mean and standard deviation of morphological traits of *S. halepense* samples in the surveyed sites. (a) Plant height. (b) Length of inflorescence (spike length). (c) Plant dry weight. (d) Leaf length. (e) Leaf area. (f) Leaf dry weight. (g) SLA. Different letters indicate significant differences among sites according to the *post hoc* test of Tukey ($p < 0.05$; ANOVA).

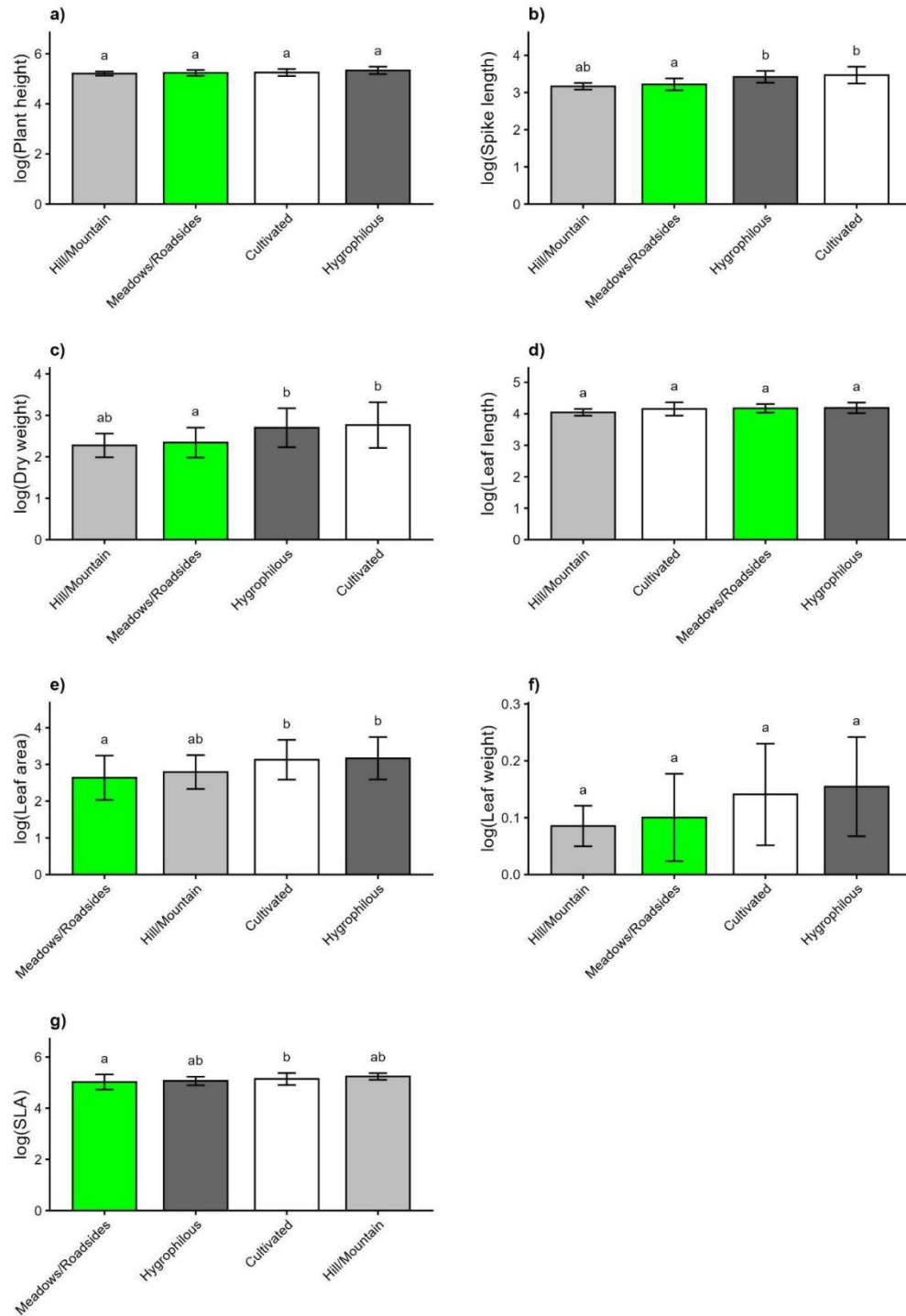


Figure 5: Bar charts showing the log of mean and standard deviation of morphological traits of *S. halepense* samples in the different habitats. (a) Plant height. (b) Length of inflorescence (spike length). (c) Plant dry weight. (d) Leaf length. (e) Leaf area. (f) Leaf dry weight. (g) SLA. Different letters indicate significant differences among sites according to the *post hoc* test of Tukey ($p < 0.05$; ANOVA).

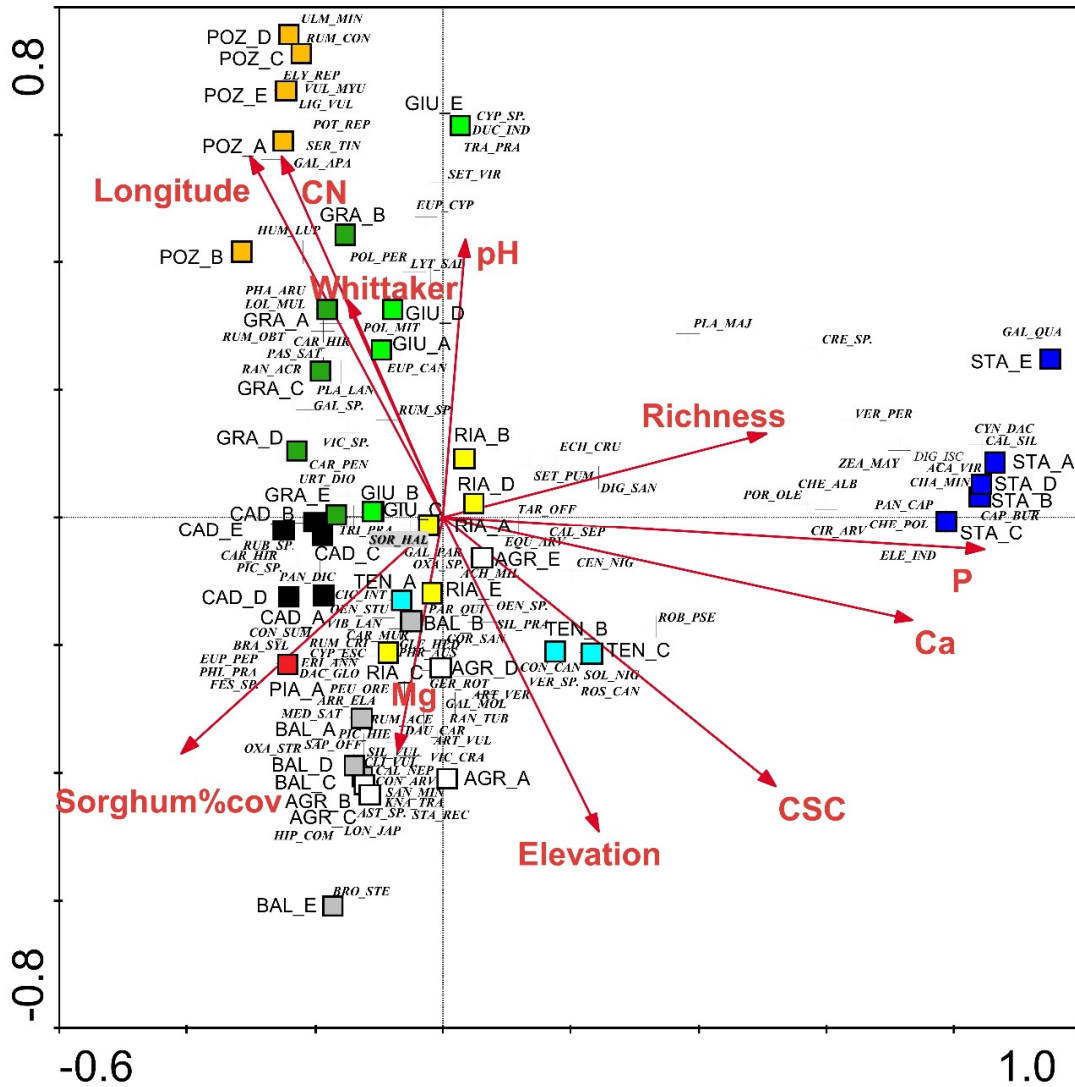


Figure 6: Scatter plot depicting the result of CCA. The distribution of species (crosses) and surveys (colored squares) is shown in relation to the different environmental variables considered (red vectors).

Table 1: Variance values of species-environment relations explained by the four canonical axes of the scatter plot, expressed as percentages.

Axes	1	2	3	4	Total Inertia
Eigenvalues	0.437	0.393	0.333	0.292	6.37
Species-environment correlations	0.946	0.936	0.922	0.899	
Cumulative percentage variance of species data	6.9	13.0	18.3	22.8	
Cumulative percentage variance of species-environment relation	16.1	30.6	42.9	53.7	
Sum of all eigenvalues					6.37
Sum of all canonical eigenvalues					2.709

Table 2: Variance values, expressed in significance levels, for each environmental variable by conditional (additive) effect.

Variable	LambdaA	p-Value	F
P	0.39	0.001	2.76
Elevation	0.32	0.001	2.27
Richness	0.29	0.001	2.22
Ca	0.28	0.001	2.13
Longitude	0.29	0.001	2.27
pH	0.24	0.004	1.98
Whittaker	0.24	0.002	1.97
CSC	0.20	0.010	1.69
Mg	0.18	0.055	1.54
Cover Sorghum	0.14	0.158	1.28
C/N	0.14	0.236	1.19

3.3 Assessments of Invasive Potential and Impacts

A total of 51 publications concerning the spread potential and the negative impacts of *S. halepense* included relevant information allowing assignment of percentage scores to the assessment's criteria and to support the discussion of the species' invasive potential (Table 3). For the impact assessment, 11 and 17 publications provided relevant information, allowing classification into an EICAT and SEICAT category, respectively (Table 3).

Table 3: Scoring of assessments on the spread and impact potential of *Sorghum halepense*. Sources used and scores are listed for each criterion of the InfoFlora Catalogue of Criteria [54] and for the EICAT [58] and SEICAT [59] procedures. Notes explain the rationale behind the scoring. The EICAT/SEICAT score given corresponds to the maximum impact category among the listed sources.

Assessment	Score	Notes	Sources
Sexual reproduction	High = 75% Medium = 25% Low = 0%	The species produces >1000 seeds per plant and the viability is >5 years but is less if seeds are buried not too deeply and the soil is managed.	[60–70]
Vegetative reproduction	High = 100% Medium = 0% Low = 0%	Vegetative reproduction occurs above and below ground, large and deep rhizomes allow strong lateral expansion.	[15,28,62,65,71,72]; personal observations
Spread by natural factors	High = 0% Medium = 50% Low = 50%	Dispersal of seeds often occurs within 10 m, but water or animals can transport them much further.	[16,60,61,65,67,73,74]; personal observations
Spread by human factors	High = 75% Medium = 0% Low = 25%	In the past the species was spread all over the world as forage crop species; it can be dispersed over tens of km by vehicles and trains in communication routes, and over tens of meters by agricultural machinery in invaded fields.	[10,11,15,16,19,60,65,71,75–78]; personal observations

Table 3: Cont.

Assessment	Score	Notes	Sources
Spread potential	High = 75% Medium = 25% Low = 0%	A rapid doubling of the area colonised and/or of the population in ≤10 years throughout Switzerland is very likely, but the species still requires relatively high temperature to germinate.	[20,22–25,36]; personal observations
Impact on human and/or animal health	High = 25% Medium = 50% Low = 25%	While the impact on human health is negligible, livestock could be intoxicated and die if plant is ingested when stressed or damaged.	[65,67,79–85]
Impact on native and endangered species	High = 0% Medium = 100% Low = 0%	The species suppress (by direct competition) and inhibit (by allelopathic substances) the growth of native plants, but in the Insubric region it is still restricted to anthropogenic and semi-natural habitats.	[16,35,36,86–92]; personal observations
Impact on vegetation structure, composition, habitat and ecosystem functions	High = 0% Medium = 100% Low = 0%	The species alters vegetation structure (by its size), composition (creating invaded monocultural habitats), and biogeochemical characteristics of soil (by allelopathic substances and nitrogen-fixing bacteria), but in the Insubric region it is still restricted to anthropogenic and semi-natural habitats.	[16,29,35,36,86,88–92]; personal observations
Impact on infrastructures	High = 0% Medium = 0% Low = 100%	The species may reduce visibility on roads, but this is easily prevented by maintenance operations.	[67]
Impact on agriculture	High = 50% Medium = 50% Low = 0%	The species causes severe crop losses and quality reduction, and can host numerous agricultural pathogens; however, it could be controlled through specific agricultural practices.	[11,16,23,26–29,65,67,93]; personal observations
Overall invasive potential	High = 40% Medium = 40% Low = 20%	Overall invasive potential based on aggregate scoring across all criteria.	
EICAT	Moderate (MO)	The species leads to a decrease in the resultant number of mature individuals within the native population.	[29,35,36,86–92]; personal observations. Source supporting the maximum impact: [90]
SEICAT	Major (MR)	The species leads to severe crop losses that may force the abandonment of the cultivated field.	[11,16,22,26–29,65,67,79–85,94]. Source supporting the maximum impact: [23]

4 Discussion

Our study is the first to reconstruct the invasion history of *S. halepense* across the Insubric region, where its presence was first documented by herbarium specimens from 1883. Since then, the species has spread throughout the region and along the lowlands of the Prealpine valleys of the southern Alps, progressively expanding northward and colonising increasingly higher elevations. This pattern is consistent with the rapid spread of the species documented elsewhere in Central Europe, favoured by current climate warming (e.g., [19,21,23]). We discuss its invasive potential and impacts across the Insubric region and elsewhere in Italy and Switzerland.

4.1 Introduction, Spread History and Current Distribution of *Sorghum Halepense*

In Italy, *S. halepense* was reported for the first time in 1561 [37], although it is likely to have occurred earlier, as it is considered an archaeophyte (i.e., introduced before the discovery of America) by several authors [17,18]. According to our analyses of herbarium specimens, the spread of *S. halepense* in the Insubric region began in the late 1800s. This is when the species reached the region during its northward range expansion from populations occurring further south in the Po Valley, where it was already widespread at least a century earlier. In other areas near the Alps and the Po Valley, such as in Trentino-Alto-Adige and around Lake Garda, the species also began to expand northward in the mid-19th century, reaching latitudes further north than Bolzano in the last decade [39,94]. The second half of the 19th century is also when *S. halepense* started to appear in other Central European countries, such as Austria, Slovakia, Slovenia, and Hungary [10,11,19,23].

Increased trade in those years likely played a key role in the spread of the species. For instance, one of the most reported pathways of introduction of *S. halepense* in Europe is as a contaminant of agricultural products, such as seed or fodder [11,23,95]. In Canton Ticino, it was introduced unintentionally as well [79], but apparently also deliberately as a fodder species. Indeed, an article published in 1894 in an agricultural magazine (i.e., *Agricoltore Ticinese*) encouraged the cultivation of the species in the canton, describing it as a hardy and vigorous fodder plant, and the editors even provided the seeds [96]. However, we found no additional historical information about its use as a fodder plant elsewhere in the Insubric region (while it certainly was in the United States [16]), and in several countries of Oceania and South America [10]. Agricultural practices may have contributed to the spread of the species, but unintentional transport seems to be the main cause. This is supported by the fact that, by the end of the 19th century, connections were already in place between towns near the Po Valley and those in Canton Ticino. Furthermore, in the last decades, an increasing number of field specialists have alerted authorities about a rapid spread of *S. halepense* in the Insubric region [79], which seems to be confirmed by the dataset analysed in this study.

A lag-phase (or stabilisation phase, i.e., between the time of introduction and the start of exponential spread; [53,97]) of approximately 100 years for many invasive species [98], including *S. halepense*, was found in Central European countries such as Austria and Slovakia [19,23]. Introduced there by the end of the 19th century and once considered rare, *S. halepense* is now reported in the phase of rapid spread, especially in cultivated fields. In regions with milder climates and earlier introductions, such as northern Italy and Hungary, the species appears to be at the beginning of the saturation phase, as already described by other authors [23,53,97] and according to many personal observations of the authors in the Po Valley during 2021. In the Insubric region, our results suggest that the species is still in the phase of rapid spread, implying that further expansion is expected before reaching the saturation phase. This is also supported by the apparent benefit that *S. halepense* derives from ongoing anthropogenic climate warming, as average annual temperature is a well-documented limiting factor for its development in Central Europe [23,99].

According to the most optimistic climatic scenario, by 2050, all major agricultural areas in Europe, as well as urban areas and grasslands all over the world, will be climatically suitable for *S. halepense* [24,25]. This trend is already partially observable in Austria, Germany, and Slovenia [20,22,23], and likely plays a key role in explaining its spread also in the Insubric region, where the species is currently found at the northern limit of its climatic range south of the Alps.

Land use change and certain agricultural practices also contribute to the spread of invasive species [25,99]. For instance, in Hungary [100] and Austria [22], the distribution area of *S. halepense* has expanded following the intensification of maize cultivation. Agricultural machinery significantly contributes to the fragmentation and dispersal of rhizomes during tillage [71], and to the dispersal of seeds by combine harvesters, which may scatter them up to 26 m forward and 12 m backward from the infestation point [60]. Additionally, the use of certain herbicides, an undiversified choice of them, and incorrect application have, in some cases, led to resistance, allowing for the selection of late-emerging ecotypes [100–102]. New ecotypes can also emerge naturally due to species' high phenotypic plasticity and adaptability, as observed in Canada and Russia, where several populations developed deeper rhizomes and increased tolerance to cold temperatures [15].

4.2 Ecological Aspects of *S. halepense* in Invaded Habitats

In the Insubric region, *S. halepense* grows in the same habitats where it is considered an invasive alien elsewhere in the world: ruderal areas, cultivated fields, vineyards, canal margins, and wetlands (especially artificial ones), as well as meadows along roadsides and railway embankments [19,26]. In Switzerland, the latter two habitats are often classified within the plant alliance Arrhenatherion, indicative of low-elevation, mown grassland environments [102]. These are considered semi-natural habitats, as they are generally mown only two to three times per year and can support a relatively high floristic diversity of notable biological value [102–104]. Even in the Insubric region, such habitats can host plant species of conservation interest [105]. Thus, to our knowledge, the present study may be the first in Europe to show that *S. halepense* is able to colonise semi-natural habitats. Furthermore, in Switzerland, areas characterised by the Arrhenatherion alliance are undergoing rapid decline in locations subject to intensive agricultural management [102]. Therefore, the dominance of *S. halepense* may represent an additional threat to this habitat, where the species has already reached an average cover of 53% in the invaded sites in our surveys. However, its presence remains clearly dependent on the proximity of transport infrastructure, which facilitates continuous dispersal of seeds and propagules, particularly at higher elevations.

The ability of *S. halepense* to colonise a wide range of habitats may reflect a high degree of phenotypic plasticity, as previously highlighted by Atwater et al. [106]. Although our results showed significant differences in some morphological traits among sites and in the meadows/roadside habitat, the overall consistency of traits across other environments may indicate that the species maintains performance across contrasting conditions, which is consistent with a generalist ecological strategy. However, the lack of significant differences in other morphological parameters among habitats supports the species' adaptability to a wide range of environments, with the species' robust rhizomes ensuring drought resistance, functioning also as water and nutrient storage organs [107].

Results of CCA showed a negative correlation between species richness and the cover of *S. halepense*, suggesting that size-based competition is one of the most effective strategies through which the species competes with and suppresses co-occurring species [36]. Although Rout et al. [86] identified *S. halepense* cover as a major factor influencing species richness in invaded sites, in our study this parameter was not statistically significant.

The negative correlation between sites hosting individuals with greater biomass and size and the altitudinal gradient confirms the thermophilic nature of *S. halepense*. Conversely, the negative correlation between the species' occurrence and the presence of nutrients such as phosphorus and calcium is not clearly explainable. Rout and Chrzanowski [86] observed that soils long invaded by *S. halepense* tend to show higher nutrient concentrations, likely due to the species' ability to produce certain chemical elements through association with specific bacteria, as well as allelopathic substances that alter the soil geochemical properties. This finding suggests that *S. halepense* could potentially gain a competitive advantage and thrive even in originally nutrient-poor soils.

4.3 Invasive Potential: Spread and Impact

Sorghum halepense is considered a noxious invasive alien species in many countries around the globe [10,11], but is not yet blacklisted in Europe and in the Insubric region, where its potential spread and impacts may currently be underestimated. We now review and discuss the ecological characteristics that contribute to the species' rapid spread and the negative impacts that it can cause, following the order of the InfoFlora Criteria Catalogue [54]).

Spread potential is estimated based on four criteria. First, sexual reproduction is high in *S. halepense*: the species is typically self-pollinating [61], producing an average of 28,000 [62] and up to 100,000 seeds per plant [63]. These remain dormant in the first year [60,64] and viable for up to 7 years in dry locations [65], with viability decreasing to 50% after 5 years [66,67], or none after 2.5 years if buried less than 20 cm deep [68] or in managed soils [69]. Local spread occurs predominantly through horizontal vegetative growth [15,65,69], thanks to its thick and deep rhizomes and roots, 40 to 90 m long (per individual plant) and bearing numerous new potential shoots [62]. Individuals developing from rhizomes are more competitive, emerge earlier, grow faster, and have a higher fresh weight than seed-derived individuals [28]. Rhizomes tolerate desiccation as well as frosty days and sprout with temperatures as low as 15°C (maximum between 23 and 30°C; e.g., [15,72]). In addition, seed dispersal ranges from within a radius of a few meters by gravity [15] to considerable distances carried by water, wind, or animals (e.g., [65]), with measured water transport of at least 400 m [73]. Seeds are transported on the animals' fur thanks to sticky appendages or manage to pass unaltered through the digestive tract of most herbivores [61,65].

Human activities strongly contribute to the long-distance dispersal of *S. halepense*, with agriculture among the most significant due to past cultivation as a forage crop (e.g., [10,19]). After tillage and threshing operations, invaded fields agricultural machinery can transport seeds and rhizomes tens of meters away [75]. Seeds are also dispersed along major roads unintentionally by vehicles (in truck loads or attached to tyres or interior mats) and by turbulence from vehicle and railway traffic [76,77]. An estimate of the spreading speed of the species in the region of interest is the last criterion to assess spread potential. In our case, based on our distributional dataset, we estimated that *S. halepense* increased its invasion front by expanding about 30 km northwards in a dozen years in Canton Ticino, which is considered to be fast. In sum, taken all together, information about the spread criteria indicates that the spread potential of *S. halepense* is to be considered primarily high (75%) and to a lesser extent medium (25%), because of the relatively high temperature (>10°C) required for successful germination [36], which currently impedes invasion of cooler areas up north or at higher elevations.

Impact assessment considers a multitude of negative impacts documented for *S. halepense*. Impacts on human health are considered 'low' according to the Catalogue of criteria [54]; even if its pollen was shown to prompt allergic reactions [80–82], in Canton Ticino this seems not to be a problem [79]. Furthermore, substances secreted by the plant are of concern only if ingested by livestock. In case of damage and stress

(drought, frost, injury to tissue cells) the plant produces hydrocyanic acid from dhurrin, which is toxic to livestock [65,67,83,84]. During August 2022, the Piedmont region (N-Italy) experienced drought and tropical temperature conditions that resulted in the deaths of sixteen cows, intoxicated after ingesting *S. halepense* [85].

Impacts on native species and ecosystems primarily occur through competition and progressive displacement. Although its seeds typically germinate later due to higher temperature requirements [36], the species gains a rapid size advantage in just two to three weeks [87]. Once established, it is able to suppress the growth of native plants by outcompeting them for essential resources (light, water, and nutrients). This competitive interaction can lead to biomass reduction of up to 95% in native species compared to individuals grown without *S. halepense* [36]. Neighbouring species can also be inhibited by allelopathic substances [16], like dhurrin [88] and sorgoleone [89], which alter soil biochemistry [35,86,90], modify the soil bacterial composition and thus nutrient availability [35,90–92]. In addition, roots and rhizomes bear nitrogen-fixing bacteria that also modify the biogeochemical characteristics of soil [86]. However, soil analyses in invaded areas show diverging effects, with either an increased availability of all nutrients except calcium [86] or a reduced availability of nutrients [90]. Results from our analyses appear to be consistent with the latter case, as sites with the most developed individuals and the highest *S. halepense* cover showed a significantly lower amount of nutrients. Impacts at the species level and on soil biochemistry are reflected at the habitat level. In the United States, species richness of semi-natural habitats is significantly lower when *S. halepense* is present [35]. About 80% of the prairie areas in the country are potentially colonizable by the species and, where already present, it spreads about half a meter per year, creating transitional environments at first and stably invaded habitats later, with a mean cover of 77% [29–35]. In our study, *S. halepense* mean cover was 53% in meadows/roadsides habitats, and species richness was lower in the plots where the species showed the most pronounced functional traits, although no direct comparisons were made with non-invaded sites. Overall, impacts on native species and ecosystems in the Insubric region appear as relevant as highlighted for other invasive species occupying ruderal habitats (i.e., *Senecio inaequidens*; [108]); however, the studied species is still restricted primarily to anthropogenic habitats and secondly to semi-natural habitats. According to the EICAT [58], such a decline in the number of individuals within native communities corresponds to a ‘Moderate’ (MO) impact category (see Table 3).

Impacts of *S. halepense* on agricultural systems are the most studied, due to the massive economic damage through crop losses (e.g., [16,26,29]) and crop quality reduction [16]. Corn and soybean (followed by cotton [93]) are the most affected crops, with crop loss ranging between 57 and 88% [28] and between 59 and 88% [27], respectively. In Austria, corn and seed pumpkin crop loss reached an average of 40% in 2013 [23]. In terms of economic loss, 300 million dollars per year were estimated to be lost in soybean production alone in Argentina [19] and about 165 million euros per year were spent on the control of the species in cotton production in Türkiye [109]. In the past, in the United States losses were so high that in some cases farmers completely abandoned the crops [65]. According to the SEICAT [59], severe crop loss leading to the abandonment of the cultivated field corresponds to a ‘Major’ (MR) impact category (see Table 3) for *S. halepense*. Impacts on crop fields can be exacerbated by the fact that the species can host and be a vector for numerous agricultural pathogens [16], such as insects, nematodes and especially fungi and viruses, which can cause additional damage to crop production (see full list in the Supplementary Material S4). In the Insubric region, the impact on agriculture appears significant, particularly in the Italian regions, where the species has been observed to establish dense monospecific populations along the boundaries of cultivated fields, subsequently spreading within these environments. However, agricultural practices are different between Switzerland and Italy, meaning that risk of invasion and negative impacts may differ as

well. In particular, crop rotation is widely implemented in Switzerland and less in Italy, and has shown to be in some cases effective against *S. halepense* proliferation and to prevent pathogens outbreaks [11].

Finally, by combining spread and impact potential, the invasion potential (risk) of *S. halepense* can be considered medium-high in the Insubric region, as the species is quite phenotypically plastic, able to potentially affect a wide range of communities by forming dense stands and altering soil properties. To compare with other invasive species, medium-high means that the risk is not as high as fast transformers like the highly invasive liana *Pueraria lobata* or some invasive aquatic aliens, like *Lagarosiphon major* [110–112]. The potential invasion risk in agriculture appears higher than that on native biodiversity in the Insubric region. Given the projected future expansion of the species' potential suitable habitats [25], anthropogenic climate warming is expected to facilitate its invasion into currently too cold and thus unsuitable areas of the Insubric region, as already documented elsewhere in Central Europe or N-America [20,22–24,113]. Furthermore, phenotypic plasticity may enable the species to spread from anthropogenic to natural habitats. Unfertilized and extensively managed meadows and dry meadows in sub-montane areas both host a higher-value biodiversity that may risk invasion by *S. halepense*.

4.4 Study Limitations

We acknowledge that our study can have some limitations associated with the limited number of sampled occurrences. Specifically, although we are confident that the analyses included in the results section (i.e., CCA) reflect field observations and actual ecological gradients, we suggest that these results be considered with caution. In addition, the analyses on biodiversity trends would have ideally followed a treatment–control approach comparing habitats with and without the presence of the species. However, we underline that across the habitats considered in this study, the species was always detected, which prevented the implementation of such a design.

5 Conclusions

In conclusion, the eradication of *S. halepense* in the Insubric region appears unrealistic (partially due to its archaeophyte status in the Italian flora). A strategy should be implemented to minimize the impact by containing its spread and reducing population density. A fundamental goal is prevention: avoiding the spread of *S. halepense* into uninvaded areas. This means identifying and tackling relevant dispersal mechanisms, which probably will result in preventive measures like avoiding the displacement of contaminated soil, careful cleaning of contaminated machinery and vehicles, and repeated mowing before flowering along roadsides and railways to minimize seed dispersal by turbulence. In any case, we call for urgent action in the Insubric region, as global warming will keep favouring the rapid spread of the species north and upwards.

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References

1. MeteoSvizzera. Rapporto sul clima—Cantone Ticino. Locarno Monti, Switzerland: Ufficio federale di meteorologia e climatologia MeteoSvizzera; 2012 [cited 2025 Jan 1]. Available from: https://www4.ti.ch/fileadmin/DT/temi/aria/clima/01_Rapporto_clima_Ticino.pdf.
2. Pautasso M. Forest ecosystems and global change: the case study of insubria. *Ann Di Bot.* 2013;3:1–29.
3. Banfi E, Galasso G. La flora esotica lombarda. Milano, Italy: Museo di Storia Naturale di Milano; 2010.
4. Schoenenberger N, Rötliberger J, Carraro G. La flora esotica nel Cantone Ticino. *Boll Della Soc Ticin Sci Nat.* 2014;102:13–30.
5. Mangili S, Parolo G, Marazzi B, Medici M, Frey D. Note floristiche ticinesi 2023: ritrovamento di una neofita nuova per la Svizzera e tre nuove per il Cantone Ticino. *Boll Soc Ticin Sci Nat.* 2023;111:49–56. (In Italian).
6. Marazzi B, Mangili S, Gygax A, Jousson A. Biology and spread of the new alien species *Coreopsis grandiflora* (Asteraceae) in southern Switzerland. *Boll Soc Ticin Sci Nat.* 2022;110:57–70.
7. Marazzi B, Rosselli A, Galasso G, Eggenberg S. *Juglans ailantifolia*. A new alien walnut tree species naturalized in Switzerland and Italy. *Boll Soc Ticin Sci Nat.* 2021;109:57–68.
8. Bellosi B, Seldorf P, Schoenenberger N. Exploring the flora on inert landfill sites in southern Ticino (Switzerland). *Bauhinia.* 2011;23:1–15. [CrossRef].
9. Fehr V, Burga CA. Aspects and causes of earlier and current spread of *Trachycarpus fortunei* in the forests of southern Ticino and northern Lago Maggiore (Switzerland, Italy). *Palms.* 2016;60(3):125–36.
10. Velez-Gavilan C. *Sorghum halepense*. In: CABI compendium. Wallingford, UK: CAB International; 2025.
11. Peerzada AM, Ali HH, Hanif Z, Bajwa AA, Kebaso L, Frimpong D, et al. Eco-biology, impact, and management of *Sorghum halepense* (L.) Pers. *Biol Invasions.* 2023;25(4):955–73. [CrossRef].
12. Lauber K, Wagner G, Gygax A. Flora helvetica: illustrierte flora der Schweiz. 4th ed. Bern, Switzerland: Haupt; 2018.
13. [USDA-ARS-NPGS] United States Department of Agriculture-Agricultural Research Service-National Plant Germplasm System. Germplasm resources information network (GRIN taxonomy). Beltsville, MD, USA: National Germplasm Resources Laboratory; 2025 [cited 2025 Jun 17]. Available from: <https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomydetail?id=35119>.
14. [POWO] Plants of the World Online. *Sorghum halepense* (L.) Pers. London, UK: Plants of the World Online (Royal Botanic Gardens, Kew); 2025 [cited 2025 Jun 17]. Available from: <https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:422139-1>.
15. Warwick SI, Black LD. The biology of Canadian weeds.: 61. *Sorghum halepense* (L.) pers. *Can J Plant Sci.* 1983;63(4):997–1014. [CrossRef].
16. McWhorter CG. History, biology, and control of johnsongrass. *Rev Weed Sci.* 1989;4:85–121.
17. Celesti-Grapow L, Pretto F, Carli E, Blasi C. Flora vascolare alloctona e invasiva delle regioni d’Italia. Roma, Italy: Università la Sapienza; 2010.
18. Galasso G, Conti F, Peruzzi L, Alessandrini A, Ardenghi NMG, Bacchetta G, et al. A second update to the checklist of the vascular flora alien to Italy. *Plant Biosyst Int J Deal Aspects Plant Biol.* 2024;158(2):297–340. [CrossRef].

19. Travlos IS, Montull JM, Kukorelli G, Malidza G, Dogan MN, Cheimona N, et al. Key aspects on the biology, ecology and impacts of johnsongrass [*Sorghum halepense* (L.) pers] and the role of glyphosate and non-chemical alternative practices for the management of this weed in Europe. *Agronomy*. 2019;9(11):717. [CrossRef].
20. Essl F. Invasion history and phytosociological affinities of Johnson grass (*Sorghum halepense*)—a case study from eastern Upper Austria. *Tuexenia*. 2005;25:251–68.
21. Weber E, Gut D. A survey of weeds that are increasingly spreading in Europe. *Agron Sustain Dev*. 2005;25(1):109–21. [CrossRef].
22. Follak S, Schleicher C, Schwarz M, Essl F. Major emerging alien plants in Austrian crop fields. *Weed Res*. 2017;57(6):406–16. [CrossRef].
23. Follak S, Essl F. Spread dynamics and agricultural impact of *Sorghum halepense*, an emerging invasive species in Central Europe. *Weed Res*. 2013;53(1):53–60. [CrossRef].
24. Kleinbauer I, Dullinger S, Klingenstein F, May R, Nehring S, Essl F. Ausbreitungspotenzial ausgewählter neophytischer Gefäßpflanzen unter klimawandel in Deutschland und Österreich. *BfN-Skripten*. 2010;275:74.
25. Yang M, Zhao H, Xian X, Qi Y, Li Q, Guo J, et al. Reconstructed global invasion and spatio-temporal distribution pattern dynamics of *Sorghum halepense* under climate and land-use change. *Plants*. 2023;12(17):3128. [CrossRef].
26. Holm L. Weeds problems in developing countries. *Weed Sci*. 1969;17(1):113–8. [CrossRef].
27. Williams CS, Hayes RM. Johnsongrass (*Sorghum halepense*) competition in soybeans (*Glycine max*). *Weed Sci*. 1984;32(4):498–501. [CrossRef].
28. Mitskas MB, Tsohis CE, Eleftherohorinos IG, Damalas CA. Interference between corn and johnsongrass (*Sorghum halepense*) from seed or rhizomes. *Weed Sci*. 2003;51(4):540–5. [CrossRef].
29. Klein P, Smith CM. Invasive Johnsongrass, a threat to native grasslands and agriculture. *Biologia*. 2021;76(2):413–20. [CrossRef].
30. Rout ME, Chrzanowski TH, Smith WK, Gough L. Ecological impacts of the invasive grass *Sorghum halepense* on native tallgrass prairie. *Biol Invasions*. 2013;15(2):327–39. [CrossRef].
31. Schwinning S, Meckel H, Reichmann LG, Polley HW, Fay PA. Accelerated development in Johnsongrass seedlings (*Sorghum halepense*) suppresses the growth of native grasses through size-asymmetric competition. *PLoS One*. 2017;12(5):e0176042. [CrossRef].
32. European Commission. Commission implementing regulation (EU) 2022/1203 of 12 July 2022 establishing a list of invasive alien species of union concern in addition to the list established by implementing regulation (EU) 2016/1141. [cited 2025 Jun 18]. Available from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R1203>.
33. [EPPO] European and Mediterranean Plant Protection Organization. EPPO lists of invasive alien plants. Paris, France: EPPO; 2025 [cited 2025 Jun 18]. Available from: https://www.eppo.int/ACTIVITIES/invasive_alien_plants/iap_lists.
34. FOEN. Alien species in Switzerland. An inventory of alien species and their impact. Bern, Switzerland: Federal Office for the Environment; 2022 [cited 2025 Jun 18]. Available from: <https://www.infoflora.ch/en/assets/content/documents/neophyten/uw-2220-e-iga.pdf>
35. Regione Piemonte. Black list–management list (gestione). Torino, Italy: Regione Piemonte; 2022 [cited 2025 Jun 18]. Available from: <https://www.regione.piemonte.it/web/sites/default/files/media/documenti/2022-10/management.pdf>.
36. Regione Lombardia. Elenco lista nera e unionali specie alloctone vegetali. Milano, Italy: Regione Lombardia; 2022 [cited 2025 Jun 18]. https://www.biodiversita.lombardia.it/index.php?option=com_content&view=article&id=296:likste-nere&catid=88&Itemid=843.
37. Saccardo PA. Cronologia della flora italiana. Padova, Italy: Tipografia del Seminario; 1909.
38. Welten M, Sutter R. Verbreitungsatlas der farn-und blütenpflanzen der Schweiz. Basel, Switzerland: Springer; 1982. [CrossRef].
39. Prosser F, Bertolli A. Atlante di 50 specie esotiche del Trentino. Rovereto, Italy: Fondazione Museo Civico di Rovereto; 2015. (In Italian).
40. Pignatti S, Guarino R, La Rosa M. Flora d’Italia. 2nd ed. Bologna, Italy: Edagricole; 2017.
41. [GBIF] Global Biodiversity Information Facility. *Sorghum halepense* (L.) pers. Copenhagen, Denmark: GBIF; 2025 [cited 2025 Jun 18]. Available from: <https://www.gbif.org/species/2705185>.

42. InfoFlora. InfoFlora—the national data and information center on the Swiss flora. Bern, Switzerland: InfoFlora; 2025 [cited 2025 Jan 1]. Available from: <https://www.infoflora.ch/en/>.
43. Ciappetta S, Ghiani A, Gilardelli F, Bonini M, Citterio S, Gentili R. Invasion of *Ambrosia artemisiifolia* in Italy: assessment via analysis of genetic variability and herbarium data. *Flora*. 2016;223:106–13. [CrossRef].
44. Eggenberg S, Möhl A. Flora vegetativa: ein bestimmungsbuch für pflanzen der Schweiz im blütenlosen zustand. 2nd ed. Bussigny, Switzerland: Rossoli; 2013.
45. Easlson HM, Bloom AJ. Easy leaf area: automated digital image analysis for rapid and accurate measurement of leaf area. *Appl Plant Sci*. 2014;2(7):1400033. [CrossRef].
46. Gentili R, Ferré C, Cardarelli E, Caronni S, Montagnani C, Abu El Khair D, et al. Performing as a transformer species? The invasive alien *Reynoutria bohemica* changes ecosystem properties in a riparian woodland. *Weed Res*. 2022;62(6):446–56. [CrossRef].
47. Hollis JM, Hannam J, Bellamy PH. Empirically-derived pedotransfer functions for predicting bulk density in European soils. *Eur J Soil Sci*. 2012;63(1):96–109. [CrossRef].
48. [USDA-NRCS] United States Department of Agriculture-Natural Resources Conservation Service. Keys to soil taxonomy. 12th ed. Washington, DC, USA: USDA-NRCS; 2014.
49. Hammer Ø, Harper DAT, Ryan PD. PAST: paleontological statistics software package for education and data analysis. *Palaeontol Electron*. 2001;4(1):9.
50. R Core Team. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2023 [cited 2025 Jan 1]. Available from: <https://www.R-project.org/>.
51. Ter Braak CJF, Šmilauer P. CANOCO reference manual and CanoDraw for Windows user's guide: software for community ordination, version 4.5. Ithaca, NY, USA: Microcomputer Power; 2002.
52. Fowler J, Cohen D. Statistica per ornitologi e naturalisti. Roma, Italy: Franco Muzzio Editore; 2010.
53. IPBES. Summary for policymakers of the thematic assessment report on invasive alien species and their control of the intergovernmental science-policy platform on biodiversity and ecosystem services. Roy HE, Pauchard A, Stoett P, Renard Truong T, Bacher S, Galil BS, et al., editors. Bonn, Germany: IPBES secretariat; 2023 [cited 2025 Mar 06]. Available from: <https://zenodo.org/record/7430692>.
54. Buholzer S, Nobis M, Schoenenberger N, Rometsch S. InfoFlora—centro nazionale di dati e informazioni sulla flora svizzera. Kriterienkatalog. Bern, Switzerland: InfoFlora; 2014 [cited 2025 Mar 06]. Available from: https://www.infoflora.ch/it/assets/content/documents/neophytes/neophytes_divers/Catalogue_des_crit%C3%A8res_2014.pdf
55. InfoFlora. Lista nera e watch list-agosto 2014. Bern, Switzerland: InfoFlora; 2020 [cited 2025 Mar 06]. Available from: https://www.infoflora.ch/it/assets/content/documents/neofite/neofite_varie/Lista%20nera_Watch%20List_2014_v2020_05_18.pdf.
56. Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, et al. A unified classification of alien species based on the magnitude of their environmental impacts. *PLoS Biol*. 2014;12(5):e1001850. [CrossRef].
57. Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, et al. Framework and guidelines for implementing the proposed IUCN environmental impact classification for alien taxa (EICAT). *Divers Distrib*. 2015;21(11):1360–3. [CrossRef].
58. IUCN. Guidelines for using the IUCN environmental impact classification for alien taxa (EICAT) categories and criteria. Version 1.1. Gland, Switzerland: IUCN; 2020 [cited 2025 Mar 06]. Available from: <https://iucn.org/sites/default/files/2023-02/eicat-guidelines-final-v1.1.pdf>.
59. Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, et al. Socio-economic impact classification of alien taxa (SEICAT). *Meth Ecol Evol*. 2018;9(1):159–68. [CrossRef].
60. Barroso J, Andújar D, Martín CS, Fernández-Quintanilla C, Dorado J. Johnsongrass (*Sorghum halepense*) seed dispersal in corn crops under mediterranean conditions. *Weed Sci*. 2012;60(1):34–41. [CrossRef].
61. Kaur R, Soodan AS. Reproductive biology of *Sorghum halepense* (L.) pers. (Poaceae; Panicoideae; Andropogoneae) in relation to invasibility. *Flora*. 2017;229:32–49. [CrossRef].
62. Horowitz M. Spatial growth of *Sorghum halepense* (L.) pers. *Weed Res*. 1973;13(2):200–8. [CrossRef].
63. Knopf FL, Scott ML. Altered flows and created landscapes in the Platte River headwaters, 1840–1990. In: Sweeney JM, editor. Management of dynamic ecosystems. West Lafayette, IN, USA: North Central Section, The Wildlife Society; 1990. p. 47–70.

64. Bennett HW. Johnson grass, dallis grass and other grasses for the humid south. In: Heath ME, Metcalfe DS, Barnes DL, editors. Forages, the science of grassland agriculture. Ames, IA, USA: Iowa State Univ. Press; 1973.
65. Holm LG, Plucknett DL, Pancho JV, Herberger JP. The world's worst weeds: distribution and biology. Honolulu, HI, USA: University Press of Hawaii; 1977.
66. Looker D. Johnsongrass has an achilles heel. *New Farm*. 1981;3:40–7.
67. Parsons WT, Cuthbertson EG. Noxious weeds of Australia. 2nd ed. Clayton South, Australia: CSIRO; 2001.
68. Concenco G, Machado LAZ, Cecon G. Espes de sorgum infestantes: importa^ço e manejo em sistemas produtivos. Dourados, Brazil: Embrapa Agropecua^{ria} Oeste; 2012.
69. Leguizamón ES. Seed survival and patterns of seedling emergence in *Sorghum halepense* (L.) pers. *Weed Res*. 1986;26(6):397–404. [[CrossRef](#)].
70. Egley GH, Chandler JM. Germination and viability of weed seeds after 2.5 years in a 50-year buried seed study. *Weed Sci*. 1978;26(3):230–9. [[CrossRef](#)].
71. Andújar D, Barroso J, Fernández-Quintanilla C, Dorado J. Spatial and temporal dynamics of *Sorghum halepense* patches in maize crops. *Weed Res*. 2012;52(5):411–20. [[CrossRef](#)].
72. Yazlik A, Uremis I. The studies on the biology of seeds and rhizomes of Johnsongrass [(*Sorghum halepense* (L.) pers.)]. *Derim*. 2015;32(1):11–30. [[CrossRef](#)].
73. Rudi G, Bailly JS, Belaud G, Vinatier F. Characterization of the long-distance dispersal of Johnsongrass (*Sorghum halepense*) in a vegetated irrigation channel. *River Res Appl*. 2018;34(9):1219–28. [[CrossRef](#)].
74. Andújar D, Rueda-Ayala V, Jackenkroll M, Dorado J, Gerhards R, Fernández-Quintanilla C. The nature of *Sorghum halepense* (L.) pers. spatial distribution patterns in tomato cropping fields. *Gesunde Pflanz*. 2013;65(3):85–91. [[CrossRef](#)].
75. Ghersa CM, Martinez-Ghersa MA, Satorre EH, Van Esso ML, Chichotky G. Seed dispersal, distribution and recruitment of seedlings of *Sorghum halepense* (L.) pers. *Weed Res*. 1993;33(1):79–88. [[CrossRef](#)].
76. Veldman JW, Putz FE. Long-distance dispersal of invasive grasses by logging vehicles in a tropical dry forest. *Biotropica*. 2010;42(6):697–703. [[CrossRef](#)].
77. [USDA-APHIS] United States Department of Agriculture-Animal and Plant Health Inspection Service. Weed risk assessment for *Sorghum halepense*. Beltsville, MD, USA: Animal and Plant Health Inspection Service; 2015.
78. McWhorter CG, Anderson JM. The technical and economic effects of Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*). *Weed Sci*. 1981;29(3):245–53. [[CrossRef](#)].
79. Schoenenberger N. Scheda descrittiva specie alloctone invasive: *Sorghum halepense* (L.) pers. Caslano, Switzerland: Tulum SA; 2011 [cited 2025 Mar 11]. Available from: https://m4.ti.ch/fileadmin/GENERALE/organismi/schede_specie/Sorghum_halepense.pdf.
80. Kearney TH, Peebles RH. Arizona flora. Berkeley, CA, USA: University of California; 1951. 1032 p.
81. Avjioglu A, Creaney J, Smith P, Taylor PE, Singh MB, Knox RB. Cloning and characterization of the major allergen of *Sorghum halapense*, a subtropical grass. In: Molecular biology and immunology of allergens. Boca Raton, FL, USA: CRC Press; 1993. p. 161–4.
82. Campbell BC, Gilding EK, Timbrell V, Guru P, Loo D, Zennaro D, et al. Total transcriptome, proteome, and allergome of Johnson grass pollen, which is important for allergic rhinitis in subtropical regions. *J Allergy Clin Immunol*. 2015;135(1):133–42. [[CrossRef](#)].
83. Henderson L. Alien weeds and invasive plants. Plant protection research institute handbook no. 12. Cape Town, South Africa: Paarl Printers; 2001.
84. Gaskill C. Johnsongrass and other sorghums can cause toxicity when grazed. *Stable Management*. 2013 [cited 2026 Jan 1]. Available from: <https://stablemanagement.com/barns-grounds/johnsongrass-and-other-sorghums-can-cause-toxicity-when-graz/>
85. Giantin S, Franzin A, Brusa F, Montemurro V, Bozzetta E, Caprai E, et al. Overview of cyanide poisoning in cattle from *Sorghum halepense* and *S. bicolor* cultivars in northwest Italy. *Animals*. 2024;14(5):743. [[CrossRef](#)].
86. Rout ME, Chrzanowski TH. The invasive *Sorghum halepense* harbors endophytic N₂-fixing bacteria and alters soil biogeochemistry. *Plant Soil*. 2009;315(1):163–72. [[CrossRef](#)].
87. Reichmann LG, Schwinning S, Polley HW, Fay PA. Traits of an invasive grass conferring an early growth advantage over native grasses. *J Plant Ecol*. 2016;9(6):672–81. [[CrossRef](#)].

88. Kovacs MT. Dhurrin (pHydroxy-mandelonitrile-Beta-D-glucoside) allelopath identified in johnsongrass (*Sorghum halepense* pers.) rhizome exudate [dissertation]. College Park, MD, USA: University of Maryland USA; 1972. 143 p.
89. Czarnota MA, Paul RN, Dayan FE, Nimbal CI, Weston LA. Mode of action, localization of production, chemical nature, and activity of sorgoleone: a potent PSII inhibitor in sorghum spp. root exudates. *Weed Technol.* 2001;15(4):813–25. [CrossRef].
90. Majumdar S, Sanwal U, Inderjit. Interference potential of *Sorghum halepense* on soil and plant seedling growth. *Plant Soil.* 2017;418(1):219–30. [CrossRef].
91. Meng QH, Huang HJ, Liu Y, Liu XG, Wei SH, Zhang CX. Chemical compositions and allelopathic potential of volatile oil from *Sorghum halepense* (L.) pers. *J Plant Prot.* 2009;36(3):277–82. (In Chinese).
92. Huang H, Wang H, Vivanco JM, Wei S, Wu W, Zhang C. Shift of allelochemicals from *Sorghum halepense* in the soil and their effects on the soil's bacterial community. *Weed Biol Manag.* 2017;17(4):161–8. [CrossRef].
93. Uludag A, Gozcu D, Rusen M, Guvercin RS, Demir A. The effect of johnsongrass (*Sorghum halepense* (L.) pers.) densities on cotton yield. *Pak J Biol Sci.* 2007;10(3):523–5. [CrossRef].
94. FloraFaunaAltoAdige. Bolzano, Italy: Naturmuseum Südtirol; 2025 [cited 2025 Jul 28]. Available from: <https://www.florafauauna.it/portal/index?locale=it>.
95. Arrigoni PV, Viegi L. La flora vascolare esotica spontaneizzata della Toscana. Firenze, Italy: Regione Toscana; 2011.
96. Unione Contadini Ticinesi. Polygonum sachalinense. *Agric Ticin.* 1984;26a:75–6.
97. Shigesada N, Kawasaki K. Biological invasions: theory and practice. Oxford, UK: Oxford University Press; 1997. [CrossRef].
98. Robeck P, Essl F, van Kleunen M, Pyšek P, Pergl J, Weigelt P, et al. Invading plants remain undetected in a lag phase while they explore suitable climates. *Nat Ecol Evol.* 2024;8(3):477–88. [CrossRef].
99. Pinke G, Blazsek K, Magyar L, Nagy K, Karácsony P, Czúcz B, et al. Weed species composition of conventional soyabean crops in Hungary is determined by environmental, cultural, weed management and site variables. *Weed Res.* 2016;56(6):470–81. [CrossRef].
100. Novák R, Dancza I, Szentey L, Karamán J. Arable weeds of Hungary: the 5th national weed survey (2007–2008). Budapest, Hungary: Ministry of Agriculture and Rural Development; 2009.
101. Johnson DB, Norsworthy JK, Scott RC. Distribution of herbicide-resistant johnsongrass (*Sorghum halepense*) in Arkansas. *Weed Technol.* 2014;28(1):111–21. [CrossRef].
102. Delarze R, Gonseth Y, Eggenberg S, Vust M. Lebensräume der Schweiz: ökologie-gefährdung-kennarten. 3rd ed. Bern, Switzerland: Ott Verlag; 2015.
103. Graiss W, Haslgrübler P, Blaschka A, Pötsch EM, Krautzer B. Establishment of an *Arrhenatherion* meadow through on-site threshing material and green hay transfer. *Grassl Sci Eur.* 2013;18:341–3.
104. Zajac M, Ujházy K, Škodová I, Kuzemko A, Borsukevych L, Danylyuk K, et al. Classification of semi-natural mesic grasslands in the Ukrainian Carpathians. *Phytocoenologia.* 2016;46(3):257–93. [CrossRef].
105. Beretta M, Brusa G. La flora di interesse conservazionistico del Lago di Annone (Lecco). *Pianura.* 2016;34:3–18.
106. Atwater DZ, Sezen UU, Goff V, Kong W, Paterson AH, Barney JN. Reconstructing changes in the genotype, phenotype, and climatic niche of an introduced species. *Ecography.* 2016;39(9):894–903. [CrossRef].
107. Acciaresi HA, Guiamet JJ. Below- and above-ground growth and biomass allocation in maize and *Sorghum halepense* in response to soil water competition. *Weed Res.* 2010;50(5):481–92. [CrossRef].
108. Quaglini LA, Yannelli FA, Fasano F, Citterio S, Gentili R. Assessing local and global ecological impacts of the alien plant *Senecio inaequidens* across different environmental conditions in Northern Italy and applying EICAT. *Weed Res.* 2025;65(3):e70019. [CrossRef].
109. Gunes E, Uludağ A, Uremis I. Economic impact of johnsongrass (*Sorghum halepense* L. pers.) in cotton production in Turkey. *J Plant Dis Prot Suppl.* 2008;21:515–20.
110. Montagnani C, Caronni S, Quaglini LA, Sebesta N, Gentili R, Citterio S. Coping with stress as a prelude of naturalization: different responses of *Lagarosiphon* species to water trophy. *Diversity.* 2023;15(5):693. [CrossRef].
111. Montagnani C, Casazza G, Gentili R, Caronni S, Citterio S. Kudzu in Europe: niche conservatism for a highly invasive plant. *Biol Invasions.* 2022;24(4):1017–32. [CrossRef].

112. Radosevich SR. Plant invasion and their management. In: Invasive plant management: CIPM online textbook. Bozeman, MT, USA: Center of Invasive Plant Management; 2002.
113. Schantz MC. *Sorghum halepense* (Johnsongrass): a review of its invasion, management, and spread in the changing climate of the southern great plains. Weed Sci. 2025;73:e31. [[CrossRef](#)].