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RESEARCH

Is *Sonchus arvensis* Capable of Further Expanding in Germany?—Assessing the Potential by Combining Literature Data with Plant Metric Data

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Abstract

Research on *Sonchus arvensis* L. is underrepresented despite its status as a widespread perennial arable weed in the Northern Hemisphere. This study investigates, based on a comparison of literature data and recent plant metric data, whether there are indications of a problematic expansion in Germany and identified two knowledge gaps. The recent plant metric data were taken between 2019–2024 at various sites in Germany, Norway, and Finland. We structured the results in subchapters along the life-stages of *S. arvensis* given in their headings: 'Propagules in the soil', 'Plant establishment', 'Rosette growth', 'Plant height', 'Seed production' and 'Plant senescence'. In Germany, *S. arvensis* has a rosette diameter measuring 34–58 cm and a height of 40–98 cm, although a height of up to 220 cm has been recorded in 2024 in Germany. Rosette diameter and plant height data indicate at least no smaller sizes compared to studies and plant metric data from other countries. Notably, 142 seeds per head were counted in Germany, indicating a source for successful spatial spreading. We address two knowledge gaps related to the research question in the title. One regarding whether vegetative growth contributes to the spread of *S. arvensis*, and another concerning how its phenological development is influenced by temperature and photoperiod. In addition, we recommend monitoring the species biology and ecology on agricultural fields in Germany.

Keywords Perennial sow-thistle · Perennial plant · Plant distribution · Weed biology

The video on 'Lifecycle animation of *Sonchus arvensis* L. (Perennial sow-thistle)' (Defant et al. 2024) is accessible at https://www.youtube.com/watch?v=IKTOTe3o1XQ&t=1s.

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Introduction

Sonchus arvensis L. (Perennial sow-thistle) is a deep-rooting perennial C_3 herb, a member of the *Asteraceae* (*Compositae*) family (Lemna and Messersmith 1990). *Sonchus arvensis* has two subtypes: *S. arvensis var. arvensis* and *S. arvensis var. glabrescens*. Both develop vegetative roots and many seeds, making them relevant as perennial weeds in arable fields (Lemna and Messersmith 1990).

Geographically, *S. arvensis* is native to Europe and has spread to America, Iceland, and Western Asia (Lemna and Messersmith 1990). It is most problematic weed in temperate zones like Northern Europe (Liew et al. 2013; Brandsæter et al. 2020), occurring less frequently in Central Europe and rarely in Southern Europe (Boulos 1973; Lemna and Messersmith 1990). In North America, *S. arvensis* is frequently found in cereals and oilseed crops (Peschken et al. 1983; Lemna and Messersmith 1990). In Saskatchewan and Manitoba (Canada), it was recorded in 39% of oilseed rape fields (Peschken et al. 1983; Lemna and Messersmith 1990). However, the weed was more abundant in barley and oats than in wheat and was more common in winter wheat than in spring wheat (Thomas and Wise 1983, 1987, 1988). Additionally, *S. arvensis* was found in 11% of surveyed fields in North Dakota, with an average density of 5.5 plants per m^2 (Dexter et al. 1981). In Asia, *S. arvensis* is even cultivated as a crop and used as a vegetable and medicinal herb. The extract of *S. arvensis* contains various compounds, including flavonoids (Khan 2012) and triterpenoids (Putra et al. 2013 cit. in Melati et al. 2021), known for their antioxidant properties, as well as triterpenoids with antibacterial effects (Rumondang et al. 2013 cit. in Melati et al. 2021). *Sonchus arvensis'* high productivity is utilised in cultivation, and it can be harvested several times above ground without destroying the roots (Melati et al. 2021; Raisawati et al. 2023). However, its regenerative capacity makes it particularly difficult to manage as a weed in agricultural systems.

Withdrawing herbicide active ingredients from the market, using lower herbicide dosages, and increasing reduced tillage are reasons for changes in the weed flora of Nordic European countries (Andreasen and Streibig 2011; Salonen et al. 2013, 2023). One outcome has been the rise of *S. arvensis*, which has gained a foothold, especially in organic farming systems where weed diversity is high (Anbari et al. 2015). Twenty years ago, in Finland, the species was found to become more abundant (Hyvönen and Salonen 2002; Salonen et al. 2001a). There, the frequency of some perennial weeds, for example, *S. arvensis* increased in line with the overall weed diversity (Riesinger and Hyvönen 2006; Salonen et al. 2001b). In Finland, *S. arvensis* currently occurs on 58% of organic fields, while on 28% of conventional fields (Salonen et al. 2023). Hence, the species is described as being primarily associated with organic production both in terms of frequency and in terms of density (Salonen and Hyvönen 2002).

Similar changes in management are common in German arable farming. Within the last 30 years, the area in organic farming has grown to 11.4% of Germany's total agricultural land (Kuhnert 2024), and the target is to increase organic farming to 30% by 2030 (Federal Ministry of Food and Agriculture 2023). In Germany, organic farmers reported on an increase in weed infestations caused by thistle species (Andert et al. 2023). Besides *Cirsium arvense* (L.) Scop., the main thistle species in Germany also include *S. arvensis*. However, comparable data on the abundance of *S. arvensis* are missing for Germany. However, Hanzlik and Gerowitt (2012) did not confirm high infestations of *S. arvensis*. The competitive success of *S. arvensis*, in particular, is traced to its adaptive characteristics: rapid growth supported by a vegetative root system, prolific seed production, and efficient nitrogen uptake early in the season (Lemna and Messersmith 1990; Eckersten et al. 2010).

This study aims to investigate whether *S. arvensis* has the potential to further expanding in Germany. Prior to extended experiments, we collected international literature data on the species. From the total collection, we selected those sources containing plant metric data of the plant life stages of *S. arvensis*. The plant metric data from Norway and Finland allowed us to compare these with German plant metric data for validity. Hence, we conducted a study in which we combined review elements with plant metric data from three countries, focusing on the species' potential for problematic expansion in Germany. This combination best serves our research question and helps to identify knowledge gaps for subsequent experimental activities and offers preliminary insights into the potential for expansion of *S. arvensis* in Germany.

Material and Methods

Activities were carried out as part of a joint project focusing on arable perennial weeds. Engaged institutions and expert scientists from five countries provided access to both international and national literature and field data observations during the project (Zhang et al. 2020).

Literature Data

Results from an extensive literature review were compiled into an indexed article database. A comprehensive literature search was conducted using the databases Web of Science, Scopus, and Google Scholar to collect relevant publications on *S. arvensis*. The search terms included combinations of keywords such as '*Sonchus arvensis*' and 'perennial sowthistle'. There was no limitation regarding the year of publication, and all relevant literature sources until 2025 were included. Studies published in English, German, Finnish, Norwegian, French, and Danish were collected. The article database contained 75 literature sources on *S. arvensis* which were qualitatively and quantitatively explored for this study (Table 4). The article database emphasizes how *S. arvensis* sustains itself under arable conditions, though perspectives from other agroecological systems, such as grasslands or road verges, were also included. Information on arable management practices employed in the studies were included only when they specifically addressed the plant life stages of the species. Most of the cited references did not provide information on the *S. arvensis* subtype. Since we follow the review on *S. arvensis* by Lemna and Messersmith (1990), we provide their herbarium codes[1].

[1] Herbarium specimens from ACAD, CAN, DAOM, DAS, HAM, LKHD, MT, NBM, NFLD, NSAC, PMAE, QFA, QUE, SASK, SCS, SFS, TRTE, UBC, USAS, UVIC, UWO, WIN, and WOCB, as well as information provided by ALTA, QK, UNB, V, and WAT (herbarium abbreviations as in Holmgren et al. 1981).

For the life stage 'Seed production', we used literature data in a simple Eq. 1 to calculate the number of seeds per seed head and incorporated additional literature sources that have not counted the number of seeds per head.

$$\text{Number of seeds per head} = \frac{\text{Number of seeds per plant}}{\text{Number of heads per plant}} \quad (1)$$

Recent Plant Metric Data

Plant metric data were collected on *S. arvensis* plants between 2019–2024, including sites in Germany, Norway and Finland (Table 5). In the present study, the *S. arvensis var. arvensis* subtype with glandular hairs on the heads was examined. This data collection included morphological measurements on growing plants and stored plant material. We distinguished between two pre-experimental studies and recent measured plant metric data collected from outdoor experiments. We used often recorded plant data that are usually not published, such as plant height and rosette diameter.

The first pre-experiment was conducted to observe the sprouting ability of *S. arvensis* ramets. Roots of varying lengths between 5–30 cm were stored in a climate chamber at +3–5 °C for 12 months. The storage of roots from *S. arvensis* was carried out in several sites and countries. After retrieving the ramets from the storage, sprouting ability was measured at room temperature (15–20 °C).

The second pre-experiment was a germination test with three *S. arvensis* populations from German sites: Rostock, Braunschweig and Uelzen (for site information see Table 5). Seeds from each population were collected in August 2024 and sown in 30 replications in soil placed in seedling trays with a size of 7 cm × 7 cm. The seeds were kept in a climate chamber with a 12/12-hour light/dark cycle and a constant temperature of 24 °C. After 4 weeks, the seeds had not yet germinated, so the temperature was increased to 25 °C. After an additional two weeks, only a few seedlings had emerged from the seeds. Consequently, the temperature was raised to 27 °C, which led to a sufficient germination of the *S. arvensis* seeds after 4 days.

The metric data on rosette diameter and plant height of *S. arvensis* were measured at different sites in Germany, Norway, and Finland at the beginning of the flowering period (Table 5). To determine the rosette diameter, the distance between the two widest, opposite points of the rosette was measured, ensuring that the ruler passed through the centre of the rosette. The plant height was recorded at the highest point of the plant, without stretching *S. arvensis*. Since most literature data report only average values or ranges of values for rosette diameter and plant height, our results were presented as ranges, showing the minimum and maximum values observed.

The number of seeds per seed head of *S. arvensis* plants was counted at the beginning of seed formation growing period (Table 5 gives site, setup information and dates of measurement). Before harvesting the seeds of *S. arvensis*, seed heads were carefully examined to ensure that the seed head was ball-shaped and that no seeds were missing. Three seed heads were collected from each of the five plants. Fertile seeds per seed head were counted and provided as average value.

We also recorded phenological development stages, including sprouting, flowering, and withering, under natural growing conditions between 2019–2021 in Rostock, Germany, as well as during the same growing period in Ås, Norway and Jokioinen, Finland and present them as observation dates.

The collected data on *S. arvensis* rosette diameter and plant height allowed statistical analysis. The agricolae package in the R-software (R version 4.4.0.) was used (De Mendiburu 2021). First, normality of the data distribution was assessed (Shapiro-Wilk test). If the data followed a normal distribution, an analysis of variance (ANOVA) was conducted. Subsequently, a least significant difference (LSD) test was applied to compare mean values and to identify significant differences. If the data were not normally distributed, a Kruskal-Wallis test was applied. We only use the term 'significant' in the text when a statistical test has been conducted, with significance accepted at $p \leq 0.05$.

Results

We structured the results in subchapters along the life-stages of *S. arvensis*: 'Propagules in the soil', 'Plant establishment', 'Rosette growth', 'Plant height', 'Seed production', and 'Plant senescence'. Each life-stage subchapter starts with the literature data, followed by the results of the collected plant metric measurements. If the data allow for a comparison between literature data and own recent plant metric data, the two data sets are linked in a table.

Propagules in the Soil

Reviewed Data

Propagules in the soil are either vegetative roots or seeds (Zollinger 1989; Anbari et al. 2016).

Vegetative roots of *S. arvensis* are located 5–12 cm deep in the soil (Arny 1932), originating from branched, shortened spindle-shaped primary roots (Korsmo 1954) and typically have a diameter of 0.25–0.5 cm (rarely reaching 1 cm) (Arny 1932). Vertical roots of *S. arvensis* have the capability to penetrate to depths of two meters (Arny 1932). The detailed maximum lifespan of vegetative roots is uncertain but is at least two years (Håkansson 1969). Vertical roots seldom survive beyond their second year (Stevens 1924; Lemna and Messersmith 1990). The root buds of *S. arvensis*, which survive the winter on either vertical or horizontal spreading roots or on the basal segments of aerial stems, can give rise to new shoots (Håkansson 1982). Ramets are fragmented roots commonly produced through soil cultivation. This usually happens in spring or autumn. Even a ramet of 2.5 cm or smaller can produce plants if well-developed buds are present, and ramets with a length of 1 cm can generate a flowering *S. arvensis* plant in less than a year (Håkansson and Wallgren 1972b). Interestingly, one *S. arvensis* plant can create a patch by propagation through its creeping root system (Anbari et al. 2015).

In natural environments, *S. arvensis* seeds are stored in the soil. Gupta and Murty (1986) found that the viability of stored seeds depended on the storage conditions and that the seed viability could be maintained at 5–7 °C for 18 months. Thompson et al. (1998) calculated the seed longevity index, which summarizes the persistence data for *S. arvensis* seeds in Northern Europe, and showed that all records are persistent for more than 1 year. We found no data on the viability of vegetative roots and ramets in soil that did not sprout.

Recent Plant Metric Data

The first pre-experiment provided information about the sprouting ability of *S. arvensis* ramets after 12 months under cold conditions. It was observed that *S. arvensis* ramets did not lose their sprouting ability.

Plant Establishment

Reviewed Data

New shoots of *S. arvensis* vegetatively sprout from root buds on roots and ramets (Håkansson 1982; Pegtel 1973). When the soil temperature increases in spring, new shoots emerge, together with the formation of new vegetative roots in the soil (Håkansson 1969; Anbari et al. 2015).

According to Håkansson (1969), most *S. arvensis* shoots emerge from the top 10 cm of the soil, although it is plausible that some shoots may emerge from a deeper soil layer. The roots close to the soil surface produce small green leaves about a week after the initial growth (Lemna and Messersmith 1990). New vegetative root growth starts approximately 3–4 weeks later (Håkansson 1969). During spring, the establishment of *S. arvensis* is impacted by temperature. Warmer temperatures in spring lead to earlier and more rapid shoot emergence than colder temperature conditions. This is due to the increased plant metabolic activity and resource allocation from roots to shoots at higher temperatures (Torssell et al. 2016; Verwijst et al. 2013). The emergence time of shoots from *S. arvensis* roots is influenced by root weight (Torssell et al. 2015, 2016). Heavier roots require a smaller temperature-sum for shoot emergence, meaning they sprout faster under the same environmental conditions compared to lighter roots (Torssell et al. 2015). Under field conditions, sprouting capacity continues throughout the season but declines from late summer to early autumn (Håkansson 1969; Håkansson and Wallgren 1972a; Brandsæter et al. 2010).

Sonchus arvensis seeds do not germinate until the soil reaches a suitable temperature, and most of seedlings typically emerge in May (Lemna and Messersmith 1990). In Canada, it was reported that *S. arvensis* seeds germinated in July (Chepil 1946). Most studies show that 25–30 °C is an ideal temperature for germination of *S. arvensis* from seeds (Stevens 1924; Håkansson and Wallgren 1972a; Pegtel 1973; Zilke and Derscheid 1959).

Seeds of *S. arvensis* typically do not display much endogenous dormancy, meaning many seeds can germinate either immediately or shortly after reaching their maturity (Dorph-Peterson 1924). In fact, approximately 80% of the seeds that germinated in the field over a span of 3–5 years did so within the first year (Brenchley and Warington 1930; Roberts and Neilson 1981). Seeds of *S. arvensis* do not require light for germination, but light stimulates germination (Pemadasa and Kangatharalingan 1977).

Recent Plant Metric Data

During 2020–2024 in Germany, *S. arvensis* sprouted from vegetative roots between April and early May, after some warm days. In Norway 2021, the first plants from vegetative roots emerged in mid-May and in Finland one week later. We observed that plants established from vegetative root sprouted earlier in the year than plants originating from seeds.

Seedlings of *S. arvensis* typically emerged after a few warm days with temperatures exceeding 25 °C. In Germany, the first seedlings were observed at the end of May. In both Germany and Norway, additional seedlings were found in early September following another period of warm weather.

The germination behavior of *S. arvensis* was checked in the second pre-experiment described above (Material and Methods). The germination test confirmed that seeds did not germinate below a temperature of 25 °C.

Rosette Growth

Reviewed Data

The vegetative plant growth of *S. arvensis* starts after full plant establishment, meaning that the sprouts or seedlings have successfully rooted and produced true leaves capable of growth, and finishes with the transition to generative reproduction. The latter is characterized macroscopically by stem elongation to develop reproductive organs. In the below-ground part, the initial thickening of new roots starts at the 5–7 leaf stage, regardless of the establishment method (Håkansson and Wallgren 1972b; Taab et al. 2018). By 3 months after the initial establishment, thickened roots have a diameter of 4 mm (Lemna and Messersmith 1990; Anbari et al. 2015). In early summer, horizontal creeping roots are developed which can exceed 2–15 m in length (Stevens 1924; Lemna and Messersmith 1990; Tørresen et al. 2010).

The literature data on rosette growth are summarized in Table 1. According to Zollinger and Kells (1991), the plants grow optimally at a day temperature of 20 °C and a night temperature of 15 °C. Under low light conditions, the rosettes became significantly larger (Zollinger and Kells 1991). Melati et al. (2021) grew plants from seeds, cut them 7 weeks after transplanting, and harvested them after 10 weeks. At that point of time, the rosettes had reached an average diameter of 55 cm.

Recent Plant Metric Data

During vegetative growth, *S. arvensis* plants produce flat rosettes. Therefore, rosette heights are low and rarely measured. Table 1 shows data on the rosette diameter from the literature and recent measurements in Germany and Norway. *Sonchus arvensis* rosette diameters between 13–80 cm were reported. In Germany, *S. arvensis* rosettes were significantly smaller in 2021 than in 2020. In Norway, rosette diameters varied in 2020 and 2021, but were within the observed range, similar to the values in 2005 (Table 1).

Plant Height

Reviewed Data

Elongation of the first stems of *S. arvensis* marks the end of the vegetative growth phase and initiates the generative development phase. Thus, stem elongation is a transition phase within the plants' growth cycle.

Flowering stems of *S. arvensis* are formed at the 12–15 leaf-stage (Håkansson 1969). Measuring stem elongation provides the quantitative trait of *S. arvensis* plant height (Table 2). The sources in Table 2 address *S. arvensis* plants established from vegetative ramets and not from seeds.

Lemna and Messersmith (1990) reviewed *S. arvensis* as a plant species that can grow to a height of 30–180 cm. Other literature sources report data within a similar range. Shorter root fragments are associated with smaller shoot heights, indicating a direct relationship between root size and shoot growth (Anbari et al. 2011, 2016). In addition, light competition plays an important role in influencing shoot height (Zollinger and Kells 1991, 1993).

A study from Denmark showed that *S. arvensis* seed shed began in mid-July in 2017 after 1262 growing degree days (base temperature was 0 °C). In 2018, shedding started in early July, after 1287 growing degree days (Bitarafan and Andreasen 2020).

Recent Plant Metric Data

Typically, in the first days of July, in Germany, Norway, and Finland, *S. arvensis* flowering starts and continues until the end of the growing season in autumn. In Table 2, plant height data is given from the literature and own measurements. In Germany, the plants grew significantly higher in 2020 than in 2021. This relationship was similar in Finland but not in Norway. The plants stopped their height growth at the beginning of flowering. In Germany in 2024, the plants

Table 1 Average measured rosette diameters of *Sonchus arvensis* in the flowering stage.

Geographical site of the experiments	Study year	Diameter (cm)	Comments	Source
USA, Michigan	1986–1987	40–80	Planted as ramets, experiment with light intensity and temperature	Zollinger and Kells (1991)
Norway, Særheim	2005	27–46	Planted as ramet, untreated semi-field, measured after cutting in autumn or with no cutting (see Table 5)	Tørresen et al. (2010), data not shown there
Indonesia, Bogor	2015	54	Planted as seedling, cut after 7 weeks and measured after 10 weeks	Melati et al. (2021)
Norway, Ås	2020	22–49	Planted as ramet in 2020	Recent plant metric data
	2021	13–64		
Germany, Rostock	2020	50–58	Planted as ramet in 2020	Recent plant metric data
	2021	34–44		
Germany, Braunschweig	2024	39–51	Vegetative roots, untreated field	Recent plant metric data

Table 2 Average measured plant height of *Sonchus arvensis* in the flowering stage.

Geographical site of the experiments	Study year	Plant height (cm)	Comments	Source
Norway	–	60–150	–	Korsmo et al. (1986)
USA, Michigan	1986–1987	33–115	Natural population in soybeans	Zollinger and Kells (1993)
USA, Michigan	1987–1988	20–138	Planted as ramet, experiment with temperature in growth chamber	Zollinger and Kells (1991)
USA, North Dakota	–	30–180	–	Pretz (1923) cit. in Lemna and Messersmith (1990)
Norway, Særheim	2005	69–70	Planted as ramet, untreated semi-field, measured before cutting in autumn	Tørresen et al. (2010)
Sweden, Uppsala	2008	76–98	Planted as ramet with different ramet sizes	Anbari et al. (2015)
Indonesia, Bogor	2015	36–93	Planted as seedling, cut after 7 weeks and measured after 10 weeks, cultivated as crop	Melati et al. (2021)
Indonesia, Surabaya	2019	64	Cultivated as crop	Wahyuni et al. (2019)
Norway, Ås	2020	50–74	Planted as ramet in 2020	Recent plant metric data
	2021	67–69		
Finland, Jokioinen	2020	71–89	Planted as ramet in 2020	Recent plant metric data
	2021	34–90		
Germany, Rostock	2020	83–98	Planted as ramet in 2020	Recent plant metric data
	2021	40–76		
Germany, Braunschweig	2024	48–61	Untreated field	Recent plant metric data
Germany, Uelzen	2024	190–220	Ramets next to field beans	Recent plant metric data

Table 3 Average number of seeds per seed head of *Sonchus arvensis*.

Geographical site of the experiments	Time	Number of seeds per head	Source
Denmark	1896–1923	30	Dorph-Peterson (1924)
Norway	Before 1930	150–200	Korsmo (1930)
USA, South Dakota	1956	60–80	Derscheid and Schultz (1960)
	1957	20–40	
Germany, Braunschweig	2024	142	Recent plant metric data

in a field with field beans grew 190–220 cm high. Notably, *S. arvensis* was smaller at the edges of the fields, probably because there was not light competition with the crop.

Seed Production

Rewieved Data

Seeds mature approximately 10 days after the onset of flowering (Anbari et al. 2015; Lemna and Messersmith 1990). The seeds of *S. arvensis* are achenes, 2.5–3.5 mm long and 1–1.5 mm wide, typically dark brown and elliptical, tapering at both ends, with 5–7 prominent ribs on each side (Lemna and Messersmith 1990). Achenes are dry, one-seeded fruits that do not open at maturity and are typical of the *Asteraceae* family. Multiple seeds are clustered together in each seed head. The white pappus, composed of soft hairs, is four times longer than the seed (Lemna and Messersmith 1990). With the pappus, the seed can easily be carried by wind or animals and spread into new areas (Anbari et al. 2015).

Sonchus arvensis is pollinated by insects (Stevens 1924) and flowers are self-incompatible (Derscheid and Schultz 1960). Seeds that are self-pollinated are usually not viable and stunted (Derscheid and Schultz 1960; Stevens 1924). Spatially isolated patches of *S. arvensis* cannot produce seeds, likely due to self-incompatibility (Stevens 1924).

Sonchus arvensis can produce between 150–240 flowers per head (Lemna and Messersmith 1990). It is unknown if every flower produces a seed. Moreover, the quantity of seeds differs among heads, plants, and locations due to various factors, including environmental conditions and the presence of appropriate pollinators (Lemna and Messersmith 1990; Stevens 1932). The literature data on the number of seeds per head are given in Table 3. Depending on the annual environmental conditions, the number of seeds per head in natural populations ranged between 20–80 seeds in two years (Derscheid and Schultz 1960). Dorph-Peterson

(1924) measured an average of 30 seeds per head in Denmark. Korsmo (1930) counted 150–200 seeds per head.

We applied Eq. 1 to calculate the number of seeds per heads of *S. arvensis* from literature sources. Stevens (1924) counted 62 heads per plant and 9750 developed seeds per plant in North Dakota, thus Eq. 1 gives 157 seeds per head. A recent study from Denmark showed that *S. arvensis* exhibits variable seed production (Bitarafan and Andreasen 2020). In Denmark, an average of *S. arvensis* plant produced about 280 seeds in 2017, while in 2018, a significantly higher number of 1954 seeds per plant was recorded (Bitarafan and Andreasen 2020). Using the number of heads per main stem from Stevens (1932) combined with the number of seeds per head and the number of seeds per plant from (Bitarafan and Andreasen 2020), Eq. 1 generates 4–31 seeds per head.

Hyvönen and Salonen (2002) demonstrated a rapid increase in the number of *S. arvensis* seedlings within 5 years in a low-input field experiment that used manure as fertilizer and excluded herbicides.

Recent Plant Metric Data

In Germany, the average counted number of seeds per head was 142 in 2024. Published and recent plant metric data observed numbers of seeds per head are given in Table 3. Quantitative measurements of fecundity data are scarce. However, the few available sources reveal an average value for Germany that is almost twice as high as in many literature sources (Derscheid and Schultz 1960; Korsmo 1930; Dorph-Peterson 1924 cit. in Lemna and Messersmith 1990). The generative reproduction of *S. arvensis* finishes when mature seeds enter the soil seedbank (see *Propagules in the soil*).

Plant Senescence

Reviewed Data

Usually, plants of *S. arvensis* start to senescence after seed shedding. At the transition from summer to autumn, above-ground vegetative growth is inhibited (Håkansson 1969). Tørresen et al. (2010) describe that *S. arvensis*, unlike *C. arvense*, stops growing in autumn and wilts very quickly. It is assumed that *S. arvensis* begins its preparations for winter earlier compared to *C. arvense* and *Elymus repens* (Brandsæter et al. 2010; Tørresen and Gerowitt 2022). Below-ground root reserves probably profit from the relocation of above-ground resources in this period. This process is expected to be influenced by day length and temperature, suggesting that a shorter photoperiod combined with higher temperatures in autumn may inhibit sprouting during that period (Liew et al. 2012; Taab et al. 2018).

Studies have suggested that *S. arvensis* roots develop an innate dormancy at the beginning of autumn, restricting ongoing sprouting from both new and old roots, even when roots are fragmented (Håkansson 1982; Håkansson and Wallgren 1972a). The dormancy period may be initiated by decreasing temperatures, the senescence of above-ground plant growth, or decreasing day length (Lemna and Messersmith 1990). Tørresen and Gerowitt (2022) reported that root fragments of *S. arvensis* did not sprout in late autumn.

Roots, either as intact system or fragmented into ramets, serve as reservoir for the new establishment of vegetative sprouts in the next year (see *Propagules in the soil*).

Recent Plant Metric Data

In Germany, we observed *S. arvensis* to start withering in September; however, late-sprouted plants, which also flowered late in the season, stayed green until early November. No data on *S. arvensis* plant senescence were collected from Germany Norway or Finland.

Discussion

In this paper, we integrated literature and recently collected plant metric data to answer our central research question. Based on our results, individual *S. arvensis* plants seem well capable to further expand on arable land in Germany. However, the presented results on the species' life stages identify knowledge gaps regarding the traits of individual plants as well as uncertainties about any spatial expansion. Findings from the literature and plant metric data directly related to life stages of *S. arvensis* are mainly addressed in the result section of this study. In this discussion section, we therefore focus on the identified knowledge gaps.

The first identified knowledge gap focuses on the vegetative growth phases in the plants' life stages. These can be influenced by factors like crop competition or nutrient availability. Biomass traits such as rosette diameter and plant height are common indicators of vegetative growth and easy to assess quantitatively. However, while increased biomass may indicate enhanced vegetative growth, it remains unclear whether this translates into higher reproductive success of *S. arvensis*. This uncertainty represents a critical knowledge gap: it is not yet known whether a prospected increase of vegetative growth under German conditions will also affect the agricultural systems and thus, will contribute to a problematic spread of *S. arvensis*.

In Norway, *S. arvensis* plants has shown increased biomass production in autumn under climate change conditions, responding more strongly to rising temperatures than to elevated CO_2 levels (Tørresen et al. 2019). Similar climatic trends are expected in Germany (Deutscher Wetterdienst 2024), suggesting that *S. arvensis* may also benefit from these altered climatic conditions.

While some plant traits growth steadily for a limited period of time, an external or internal event, such as photoperiod or growth hormones, can induces the transition to the next phenological stage of plant development. The second knowledge gap concerns this phenological development of *S. arvensis*. Phenological development can be qualitatively assessed by recording the timing (date or month) of key life stages of the plant, such as germination and sprouting, formation of flower heads and starting to wither. However, these point events are themselves also altered by environmental conditions, particularly the temperature and the photoperiod. Despite the importance of these conditions, actually knowledge about *S. arvensis*' requirements for specific temperatures and specific day-lengths as indicator for photoperiodicity is lacking as well as how those factors affect the important phenological stages of *S. arvensis.*

Seed production is a direct metric of the reproductive output of *S. arvensis* and represents a crucial link between vegetative growth and population establishment. In Germany, the seed production rate was higher than in other regions, which may be one reason why *S. arvensis* can spread effectively under German conditions. However, we still do not know how many of these seeds actually survive, germinate and develop into seedlings under crop competition in the field. Moreover, the question arises as to why the spatial spread of *S. arvensis* occurred frequently in colder regions, such as Norway and Finland, even though its seeds require high temperatures to germinate. As a species with two reproduction strategies, it is possible that in the northern regions, the plant spreads more through vegetative growth via creeping roots, whereas in the southern regions, like Germany, dispersal occurs through more seed production.

Closing these two crucial knowledge gaps would be essential to fully confirm whether *S. arvensis* plants could actually spread further rather than based on individual plant traits alone.

However, individual plant characteristics that indicate better reproduction are no guarantee that a plant will expand in space. Studies in plant biology generally aim to understand the life cycle and developmental processes of plants, the duration of observations depends on the species studied and the specific research objectives. However, literature reviews in plant biology suggest that observation periods should typically span more than 2–3 years to capture interannual variability and long-term patterns. However, for Germany, it is essential to extend the observation period to ensure more robust and representative conclusions. Thus, forecasting how the distribution in space can change would further help to answer the research question fully.

As stated, there is little data on the spatial distribution of the species on arable land in Germany to serve as a starting point. Species Distribution Models (SDMs) are useful for predicting the potential geographic distribution of *S. arvensis* based on environmental variables, and they can provide more accurate predictions when phenological data is incorporated (Zurell et al. 2024). The data collected here provides an initial basis for species distribution modelling and forecasting species occurrences in Germany, but are not sufficient on their own to deliver meaningful predictions.

Therefore, any predictions on whether *S. arvensis* will occur on arable land more frequently or in higher plant densities in the future remain uncertain. If driving forces in management, like shifting to organic farming, get stronger in space and time, both an increase in the spatial distribution and higher abundances in the field can be expected. It also remains unclear whether, and if so which, mechanical control measures could effectively limit the further spread of *S. arvensis*. However, for a perennial weed species, management details on the cropping system like crop rotation, tillage and plant husbandry are more important than just the absences of chemical control with herbicides.

Thus, fine-tuning in arable management will alter species spatial distribution. Collecting data of the current distribution on arable land to start with would assist to overcome this together with better insight into the identified knowledge gaps. Together, these data would enable better-founded predictions for the expansion of the species under climate change or land use change (e.g. prospected increase of organic arable farming) and, most importantly, under the interaction of these two.

Appendix

Table 4 List of all available literature sources on *Sonchus arvensis* from the database. The literature sources are sorted in ascending order by study year; for studies with year ranges, the first year is considered. If no study year is provided, the publication year is used instead. Additionally, the countries and cities mentioned in the studies are listed under "Geographical sites of experiments," if available. The plant life stages examined in the results section are indicated accordingly. An "X" marks whether a source contains information on a specific life stage of the plant and is used for the reviewed data.

Literature source	Geographical site of the experiments	Study Year	Plant life stages					
			Propagules in the soil	Plant establishment	Rosette diameter	Plant height	Seed production	Plant senescence
Dorph-Peterson (1924)	Denmark	1896–1923	–	x	–	–	x	–
Pretz (1923) cit. in Lemna and Messersmith (1990)	USA; North Dakota	–	–	–	–	x	–	–
Stevens (1924)	USA; North Dakota	–	x	x	x	–	x	–
Korsmo (1930)	Norway	–	–	–	–	–	x	–
Brenchley and Warington (1930)	UK; Rothamsted	–	–	x	–	–	–	–
Arny (1932)	USA; St. Paul	1931	x	–	–	–	–	–
Chepil (1946)	Canada	–	–	x	–	–	–	–
Korsmo (1954)	Norway	–	x	–	–	–	–	–
Derscheid and Schultz (1960)	USA; South Dakota	1956–1957	–	–	–	–	x	–
Vidme (1961)	Norway; Vollebekk	1956–1961	–	–	–	–	–	–
Fykse (1974)	Norway	1952–1973	–	–	–	–	–	–
Zilke and Derscheid (1959)	Canada	–	–	x	–	–	x	–
Håkansson (1969)	Sweden; Uppsala	1966–1986	–	x	–	–	–	x
Thomas and Wise (1983)	USA, Saskatchewa	1967–1979	–	–	–	–	–	–
Håkansson and Wallgren (1972a)	Sweden; Uppsala	1967–1969	–	–	–	–	–	–
Thomas and Wise (1988)	USA; Saskatchewa	1968	–	–	–	–	–	–
Håkansson and Wallgren (1972b)	Sweden; Uppsala	1968–1971	x	x	x	–	–	x
Pegtel (1973)	Netherland	–	–	x	–	–	–	–
Fykse (1977)	Norway; Ås	–	–	–	–	–	–	–
Pemadasa and Kangatharalingan (1977)	Indonesia	–	–	x	–	–	–	–
Roberts and Neilson (1981)	–	–	–	x	–	–	–	–
Håkansson (1982)	Sweden	–	–	–	–	–	–	x
Peschken et al. (1983)	North America Saskatchewa, Manitoba	–	–	–	–	–	–	–
Devine and Vanden Born (1985)	Canada; Alberta	–	–	–	–	–	–	–
Thomas and Wise (1987)	USA, Saskatchewa	1984	–	–	–	–	–	–
Schimming and Messersmith (1988)	USA; North Dakota	1985, 1987	–	–	–	–	–	–
Gupta and Murty (1986)	India; New Delhi	–	x	–	–	–	–	–
Korsmo et al. (1986)	Norway	–	–	–	–	x	–	–
Zollinger and Kells (1991)	USA; Michigan	1986	–	–	x	x	–	–
Zollinger (1989)	USA; Michigan	1986–1988	x	–	–	–	–	–
Derksen et al. (1993)	Canada; Saskatchewan	1986–1990	–	–	–	–	–	–
Zollinger and Kells (1993)	USA; Michigan	1987–1988	–	–	–	x	–	–
Boström and Fogelfors (1999)	Sweden	1988–1994	–	–	–	–	–	–

Table 4 (Continued)

Literature source	Geographical site of the experiments	Study Year	Plant life stages					
			Propagules in the soil	Plant establishment	Rosette diameter	Plant height	Seed production	Plant senescence
Lemna and Messersmith (1990)	Canada	–	x	x	x	x	x	x
Hyvönen and Salonen (2002)	Finland; Jokioinen	1992–1997	–	–	–	–	–	–
Tørresen et al. (2003)	Norway; Apelsvoll, Brandval, Norderas and Hauer	1993–2000	–	–	–	–	–	–
Streit et al. (2002)	Switzerland	1996–1998	–	–	–	–	–	–
Salonen et al. (2001a, 2001b, 2002)	Finland	1997–1999	–	–	–	–	–	–
Salonen et al. (2013)	Finland	1997–1999, 2007–2009	–	–	–	–	–	–
Thompson et al. (1998)	Netherland	–	x	–	–	–	–	–
Vanhala et al. (2002)	Finland; Vihti	2001	–	–	–	–	–	–
Vanhala et al. (2006)	Finland; Vihti	2001–2003	–	–	–	–	–	–
De Cauwer et al. (2008)	Belgium; West Flanders	2001–2004	–	–	–	–	–	–
Brandsæter et al. (2010)	Norway	2002	x	x	–	–	–	x
Riesinger and Hyvönen (2006)	Finland; Itä-Uusimaa	2002	–	–	–	–	–	–
Brandsæter et al. (2012)	Norway; Ås	2002–2006	–	–	–	–	–	–
Hyvönen and Salonen (2003)	Finland	–	–	–	–	–	x	–
Brandsæter et al. (2011)	Norway	2003–2006	–	–	–	–	–	–
Tørresen et al. (2010)	Norway; Særheim	2004–2005	–	–	x	x	–	x
Tørresen et al. (2019)	Norway; Ås	2004–2006	–	–	–	–	–	–
Tørresen and Gerowitt (2022)	Norway; Særheim	2005	–	–	–	–	–	x
Eckersten et al. (2010)	Sweden; Uppsala	2006–2007	–	–	–	–	–	–
Berestetskiy et al. (2008)	Russia; Saint Petersburg	2007	–	–	–	–	–	–
Eckersten et al. (2011)	Sweden; Uppsala	2007	–	–	–	–	–	–
Brandsæter et al. (2017)	Norway	2007–2010	–	–	–	–	–	–
Fogelfors and Lundkvist (2008)	Sweden; Uppsala	–	–	–	–	–	–	–
Anbari et al. (2011)	Sweden; Uppsala	2008	–	–	–	x	–	–
Anbari et al. (2015)	Sweden; Uppsala	2008	x	x	x	x	x	x
Anbari et al. (2016)	Sweden; Uppsala	2008	x	–	–	x	–	–
Liew et al. (2013)	Sweden	2008	–	–	–	–	–	–
Fogelfors and Lundkvist (2009)	Sweden; Upsala	–	–	–	–	–	–	–
Liew et al. (2012)	Sweden; Uppsala	2009	–	–	–	–	–	x
Verwijst et al. (2013)	Sweden; Upsala	2009	–	x	–	–	–	–
Torssell et al. (2015)	Sweden; Uppsala	2009	–	x	–	–	–	–
Torssell et al. (2016)	Sweden; Uppsala	2009	–	x	–	–	–	–
Evidente et al. (2011)	Italy; Portici	–	–	–	–	–	–	–
Khan (2012)	Pakistan; Distrikt Bannu	2011	–	–	–	–	–	–
Tavaziva (2012)	Sweden; Uppsala	2012	–	–	–	–	–	–
Brandsæter et al. (2020)	Norway; Ås	2013–2016	–	–	–	–	–	–
Melati et al. (2021)	Indonesia; Bogor	2015	–	–	x	x	–	–

Table 4 (Continued)

Literature source	Geographical site of the experiments	Study Year	Plant life stages					
			Propagules in the soil	Plant establishment	Rosette diameter	Plant height	Seed production	Plant senescence
Bitarafan and Andreasen (2020)	Denmark; Taastrup	2017, 2018	–	–	–	x	x	–
Taab et al. (2018)	Sweden; Uppsala	–	–	–	x	–	–	x
Wahyuni et al. (2019)	Indonesia; Surabaya	2019	–	–	–	–	–	–
Salonen et al. (2023)	Finland	2020–2022	–	–	–	–	–	–
Raisawati et al. (2023)	Indonesia; Bogor	–	–	–	–	–	–	–

Table 5 Sites of collected recent plant metric data. The measurements given in "Results" are here connected with the corresponding dates and the sample size of measured plants (*n*).

Site	Coordinates	Setup and environmental conditions	Date and sample size (*n*) of measurements					
			Rosette diameter		Plant height		Number of seeds per head	
			Date	*n*	Date	*n*	Date	*n*
Germany; Rostock	54.0924° N, 12.0991° E	Outdoor pots planted with one ramet per pot in 2019	2020-07-17 and 2021-07-07	25	2020-07-17 and 2021-07-07	25	–	–
Germany; Braunschweig	52.2156° N, 10.6378° E	Natural population	2024-07-16	10	2024-07-16	10	2024-08-27	15
Germany; Uelzen	53.0833° N, 10.4667° E	Natural population	–	–	2024-07-06 and 2024-08-11	7	–	–
Norway; Ås	59.6709° N, 10.7723° E	Outdoor pots planted with one ramet per pot in 2019	2020-07-17 and 2021-07-08	25	2020-07-17 and 2021-07-08	25	–	–
Norway; Særheim	58.7607° N, 5.6517° E	Outdoor pots planted with one ramet per pot in 2005	2005-09-01	12	2005-08-022	20	–	–
Finland; Jokioinen	60.8119° N, 23.4754° E	Outdoor pots planted with one ramet per pot in 2019	–	–	2020-07-17 and 2021-07-08	25	–	–

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