Effects of Nitrogen Deposition on Allelopathy of Solidago canadensis at Different Invasion Levels: Postprint

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Abstract

To investigate the mechanism by which global nitrogen deposition affects the expansion of alien plant invasions. This study employed a controlled simulation experiment, using the invasive plant Solidago canadensis L. as the subject, to examine the effects of leaf litter extracts from S. canadensis at three nitrogen levels (N0, N5, and N12) and five different invasion degrees (intraspecific and interspecific competition) on the allelopathic effects on seed germination and seedling growth of the native plant lettuce (Lactuca sativa L.). The results demonstrated that: (1) Leaf litter extracts from S. canadensis at different invasion degrees under N0, N5, and N12 treatments all significantly inhibited lettuce germination and growth. Among these, the extract from the N5 soil early invasion stage (S1A3) treatment exhibited the most pronounced allelopathic effect, with germination speed index, germination vigor index, root length, plant height, and leaf length decreasing by 61%, 79%, 84%, 68%, and 13% compared to the control, respectively. At this stage, the total phenol and total flavonoid contents in the leaf litter were highest, at 0.48 mg · g-1 and 1.50 mg · g-1, respectively. (2) Under identical nitrogen addition, invasion degree significantly influenced the allelopathy of S. canadensis; as invasion degree increased, the allelopathic effect of S. canadensis decreased significantly. The allelopathic effect of leaf litter at the early invasion stage (S1A3) was significantly higher than that at the late invasion stage (S3A1). (3) Under identical invasion degree, nitrogen addition significantly affected the allelopathic effect of S. canadensis; the allelopathic effect under N5 nitrogen deposition treatment was significantly greater than that under N0 or N12 treatments. (4) Nitrogen addition and invasion degree exhibited an interactive effect, with their combined action significantly influencing the comprehensive allelopathic effect on lettuce seeds. Therefore, nitrogen deposition may enhance the allelopathic inhibition of native plants by S. canadensis leaf litter during the early invasion stage, thereby further promoting successful

alien plant invasion. This provides a theoretical reference for further research on the allelopathy of S. canadensis and its ecological control.

Full Text

Effects of Nitrogen Deposition on Allelopathy of Solidago canadensis at Different Invasion Degrees

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Abstract

To explore the mechanism by which global nitrogen deposition influences the expansion of invasive plants, this study conducted controlled simulation experiments using the invasive plant *Solidago canadensis* L. as the subject. We investigated the effects of leaf litter extracts from *S. canadensis* at five different invasion degrees (intraspecific and interspecific competition) under three nitrogen levels (N0, N5, and N12) on seed germination and seedling growth of the native plant lettuce (*Lactuca sativa* L.). The results showed that: (1) Leaf litter extracts from *S. canadensis* at different invasion degrees under N0, N5, and N12 treatments all significantly inhibited lettuce germination and growth. The allelopathic effect was most pronounced in the N5 treatment at the initial invasion stage (S1A3), where the germination speed index, germination vitality index, root length, plant height, and leaf length decreased by 61%, 79%, 84%, 68%, and 13% compared to the control, respectively. At this point, total phenol and total flavonoid contents in the litter reached their highest values at 0.48 mg · g ^{1} and 1.50 mg · g ^{1}, respectively. (2) Under the same nitrogen addition, invasion degree significantly affected the allelopathic effect of *S. canadensis*, which decreased significantly with increasing invasion degree. The allelopathic effect of litter at the initial invasion stage (S1A3) was significantly higher than that at the late invasion stage (S3A1). (3) At the same invasion degree, nitrogen addition significantly affected the allelopathic effect of *S. canadensis*, with the N5 nitrogen deposition treatment showing significantly stronger allelopathic effects than N0 or N12 treatments. (4) Nitrogen addition and invasion degree exhibited interactive effects, with their combined influence significantly affecting the comprehensive allelopathic effect on lettuce seeds. Therefore, nitrogen deposition may enhance the allelopathic inhibition of *S. canadensis* litter on native plants during the initial invasion stage, further promoting successful invasion by exotic plants. These findings provide a theoretical reference for further research on the allelopathic mechanisms and ecological control of *S. canadensis*.

Keywords: nitrogen deposition, allelopathy, *Solidago canadensis*, litter, invasion degree

Introduction

Invasive alien plants pose a serious threat to local ecosystems and regional economies (Roxburgh et al., 2004). According to the Novel Weapons Hypothesis (NWH), allelopathy is recognized as one of the primary mechanisms facilitating the successful invasion of alien plants (Keane & Crawley, 2002; Kaur & Kohli, 2013). Previous studies have found that invasive plants such as *Ageratina adenophora*, *Parthenium hysterophorus*, and *Bidens pilosa* can input allelochemicals into invaded habitats through leaf litter or root exudates, thereby inhibiting seed germination and seedling growth of coexisting native plants or affecting their competitiveness (Chou, 2006; Hierro & Callaway, 2003; Yan et al., 2016). However, most previous research has focused on direct or indirect interactions between invasive and native plants, with little consideration of global climate change, particularly atmospheric nitrogen deposition.

In recent years, rapid urbanization and industrialization, excessive nitrogen fertilizer use, and massive consumption of fossil fuels have increased human activities, making nitrogen deposition one of the most important environmental factors affecting natural ecosystems (Liu et al., 2013). As nitrogen is one of the most limiting elements in terrestrial ecosystems, nitrogen deposition increases the availability of nitrogen in soil and nitrogen content in plants, thereby affecting plant growth, development, and various life activities. Studies have found that different species respond differently to increased nitrogen deposition. The addition of available nitrogen in soil often benefits fast-growing species that can rapidly convert nitrogen, giving them a competitive advantage (Nordin et al., 2005). Changes in nutrient resource levels caused by nitrogen deposition may have different impacts on native and invasive species. Furthermore, nitrogen deposition significantly influences species composition, interspecific competition, litter decomposition, and ecosystem functions in terrestrial ecosystems (Wang & Chen, 2019; Bobbink et al., 2010; Matson et al., 2002). Therefore, it is essential to consider plant invasion risk against the background of atmospheric nitrogen deposition.

Solidago canadensis, native to North America, is a perennial herb of the Asteraceae family. Introduced to China as an ornamental plant, it subsequently escaped into the wild and rapidly spread to become a noxious weed (Zihare & Blumberga, 2017). It is widely distributed across China, significantly altering local ecosystems and biodiversity while causing considerable economic losses. Recent studies have demonstrated that aqueous extracts of *S. canadensis* have strong allelopathic effects (Huang et al., 2013), significantly inhibiting seed germination and seedling growth of various plants including cauliflower, radish, and wheat (Huang & Ying, 2007; Yang et al., 2007; Fang et al., 2007), with inhibitory effects increasing with concentration. To date, multiple active substances have been isolated and extracted from *S. canadensis*, including volatile terpenoids, flavonoids, phenols, and essential oils, some of which exhibit insecticidal, antimicrobial, chemical defense, and allelopathic inhibition activities (Huang et al., 2012; Wu et al., 2016).

While numerous studies have simulated the effects of nitrogen deposition on plants, most have focused on plant growth morphology, biomass allocation, and leaf characteristics (Wan et al., 2018), with few reports on the effects and mechanisms of nitrogen deposition on the allelopathic potential of invasive plants. Therefore, this study used *S. canadensis* and native *Artemisia argyi* as subjects, growing *S. canadensis* under different nitrogen levels and competition intensities (intraspecific and interspecific) in a greenhouse to obtain its leaf litter (Ren et al., 2019). We examined the effects of litter aqueous extracts on seed germination and seedling growth of the native plant lettuce and measured the contents of two major allelochemicals—total phenols and total flavonoids—in the litter (Bärlocher & Graça, 2005). This study aimed to address three scientific questions: (1) Does allelopathic effect of invasive plants on native plants increase under nitrogen deposition? (2) Do allelopathic effects of invasive plant litter differ under various competition levels (intraspecific and interspecific)? (3) Do interactive effects exist between nitrogen deposition and different competition levels? The results will provide experimental evidence for further elucidating the successful invasion mechanisms of *S. canadensis*, particularly regarding the relationship between atmospheric nitrogen deposition and alien plant invasion under global nitrogen deposition scenarios, offering important theoretical foundations and guidance for effective invasion control.

1.1 Material Preparation

In late October 2016, seeds of *Solidago canadensis* and native *Artemisia argyi* were collected from open fields in the suburbs of Zhenjiang, Jiangsu Province, and stored in the laboratory under dark conditions. Soil was collected from areas where both *S. canadensis* and *A. argyi* grew naturally. The soil had a total nitrogen (TN) content of (747.10 ± 14.90) mg · kg ^{1}, nitrate nitrogen (NO -N) content of (36.20 ± 13.77) mg · kg ^{1}, and ammonium nitrogen (NH -N) content of (4.62 ± 0.56) mg · kg ^{1}.

1.2.1 Plant Cultivation and Litter Preparation

In May 2017, seeds of *S. canadensis* and *A. argyi* were sown separately in greenhouse pots (24 cm diameter, 18 cm height) containing 3 kg of soil. The atmospheric nitrogen deposition in the study area was approximately 5 g · m ^{2} · yr ^{1} (Wang et al., 2017). Therefore, nitrogen deposition treatments were set at 5 g · m ^{2} · yr ^{1} (N5) and 12 g · m ^{2} · yr ^{1} (N12) to simulate atmospheric nitrogen deposition levels expected by the end of this century. Based on pot size, N5 and N12 treatments received 0.23 g and 0.54 g of nitrogen per pot, respectively.

To maintain the global average ratio of natural atmospheric nitrogen deposition, nitrogen was applied as a mixture of KNO :NH Cl:urea at a 1:1:1 ratio, with each gram of nitrogen containing 0.47 g KNO , 0.25 g NH Cl, and 0.28 g urea (Fowler et al., 2013). To balance nutritional limitations and toxic effects (seedling burn) of nitrogen on seedlings, the nitrogen was dissolved in 100 mL of aqueous solution and added to pots over 7 weeks. The weekly nitrogen solution was gradually increased following a 1:1:1:1:2:2:2 ratio. Meanwhile, control treatments received equal amounts of distilled water. To simulate different invasion degrees (competition intensities) of *S. canadensis* in the field, five competition patterns were established: one *S. canadensis* plant (S1), three *S. canadensis* plants (S3), one *S. canadensis* mixed with three *A. argyi* plants (S1A3), two *S. canadensis* mixed with two *A. argyi* plants (S2A2), and three *S. canadensis* mixed with one *A. argyi* plant (S3A1). The S1 and S3 treatments simulated complete invasion by *S. canadensis* at different degrees (with or without intraspecific competition), while S1A3, S2A2, and S3A1 simulated early, middle, and late invasion stages (different interspecific competition intensities). Each treatment had five replicates. A total of 75 pots were used in this experiment (3 N levels × 5 planting patterns × 5 replicates). After 90 days of cultivation, *S. canadensis* leaves were carefully collected, thoroughly washed, and dried at 40°C for 72 hours.

1.2.2 Litter Allelopathy Bioassay

Thirty grams of dried leaf litter from each of the 15 treatments were soaked in 1,000 mL of distilled water at room temperature for 48 hours and then filtered. The resulting extracts ($30\ g \cdot L^{-1}$) were stored at 4°C. A distilled water control (CK) was used. The experiment included 16 treatments with five replicates each. Lettuce seeds were surface-sterilized with 1% sodium hypochlorite, and 30 plump seeds were carefully placed in petri dishes (9 cm diameter) lined with two layers of filter paper, with 5 mL of the respective treatment solution added to each dish. The petri dishes were placed in a temperature-controlled incubator for 14 days of dark cultivation. Each day, 0.5 mL of deionized water or litter extract was added to each petri dish, and the number of germinated seeds was recorded.

1.3 Index Measurement and Methods

After 14 days of cultivation, 10 seedlings were randomly selected from each petri dish to estimate lettuce seed germination and seedling growth indices. Plant height, root length, leaf length, and leaf width were measured. Seedling biomass (fresh and dry weight) was also determined.

Leaf shape index = leaf length/leaf width.
Moisture content = (fresh weight - dry weight)/fresh weight.
Germination potential = number of germinated seeds on day 3 (peak germination period)/total number of tested seeds.

Germination rate = number of germinated seeds/total number of tested seeds when no new germination occurred after 10 days.
Germination index = $\Sigma(GI/I)$, where I represents cultivation time (days) and GI represents the number of seeds germinated on that day.
Germination vitality index = germination index × seedling fresh weight.
Germination rate index = germination rate × germination index.

Response index (RI) = C/T - 1, where C is the lettuce seed germination and seedling growth index under different treatment extracts, and T is the growth index of the blank control. RI < 0 indicates inhibition, while RI > 0 indicates promotion. The sum of all RI values for the above lettuce seed growth indices represents the synthetical allelopathic index (RIS), which evaluates the allelopathic effect of *S. canadensis* litter extract on lettuce seed germination and seedling growth (Reigosa et al., 1999).

Total phenol content in *S. canadensis* litter was determined using the Folin-Ciocalteu method with gallic acid as the standard (Li et al., 2010; Orhan et al., 2012). Flavonoid content was measured using aluminum chloride with rutin as the standard (Kassim et al., 2011).

1.4 Data Analysis

Before data analysis, statistical analysis was performed to determine the normality and homogeneity of variance. Analysis of variance (ANOVA) was used to evaluate differences in lettuce seed germination and seedling growth indices, followed by Tukey' s-b test for multiple comparisons. Statistical significance was determined at P 0.05. All statistical analyses were performed using IBM SPSS Statistics (version 22.0; IBM Corp, Armonk, NY, USA).

2.1 Effects of Solidago canadensis Extract on Lettuce Seed Germination and Growth

As shown in Table 1 , leaf litter extracts of *S. canadensis* under different treatment conditions all exhibited inhibitory effects on lettuce seed germination. Under N0 treatment, litter extracts at different invasion degrees inhibited lettuce seed germination, with the S3A1 treatment reducing germination by 18% compared to CK. Under N5 treatment, the S3A1 litter extract reduced lettuce seed germination rate but not significantly, while other treatments significantly reduced germination rate. Under N12 treatment, only S1 and S1A3 litter extracts showed significant inhibition, reducing germination rate by 17% and 18% compared to CK, respectively. Differences in germination rates among the three nitrogen treatments indicated that nitrogen addition alleviated litter inhibition on lettuce seed germination to some extent. All litter extracts significantly reduced lettuce germination speed index and germination vitality index; however, no differences in germination speed index were observed among treatments. The germination vitality index was most significantly affected by the litter extract under N5 treatment at S1A3, decreasing by 79% compared to CK.

For lettuce seedling growth, *S. canadensis* extracts also showed inhibitory effects. Compared to N5 treatment extracts, the inhibitory effects on root length, plant height, leaf length, leaf width, and fresh weight were generally alleviated under N12 treatment, though different plant parts showed varying sensitivity to the extracts. Root length was most sensitive to the extracts, with all litter extracts significantly inhibiting root growth. The most significant inhibition occurred under N5 treatment at S2A2, reducing root length by 86% compared to CK. High nitrogen addition alleviated the inhibitory effect, with N5 treatment at S1 reducing root length by only 50% compared to CK. Plant height was also sensitive to extracts, with N5 treatment at S2A2 reducing height by 76% compared to CK. Other treatments significantly reduced plant height, though no significant differences were observed among them. Leaf length and fresh weight were significantly affected by extracts, but the effects were weaker. Leaf length showed the most obvious inhibition under N5 treatment at S2A2, decreasing by 22% compared to CK, while the weakest inhibition occurred under N0 treatment at S3A1, decreasing by only 7% compared to CK. Fresh weight was most significantly inhibited under N5 treatment at S2A2, decreasing by 45% compared to CK. Under N12 treatment, fresh weight decreased at S1 and S3, but the differences were not significant.

Differential inhibition among lettuce seed parts indicated that litter extracts affected cell structures of different seed parts to varying degrees. Two-way ANOVA results showed that *S. canadensis* litter significantly affected lettuce seeds under both nitrogen deposition and invasion degree treatments. Nitrogen addition significantly affected lettuce root length, plant height, germination rate, germination vitality index, and seedling fresh weight. Invasion degree significantly affected lettuce root length, leaf length, germination speed index, germination vitality index, and seedling fresh weight. Under combined treatment, the allelopathic effect of litter was slightly alleviated but still significantly affected lettuce root length, leaf length, germination vitality index, and seedling fresh weight (Table 2). These results demonstrated that *S. canadensis* litter from different treatments possessed allelopathic effects that significantly inhibited lettuce seed germination and growth.

2.2 Analysis of Comprehensive Allelopathic Effects of Solidago canadensis Extract

As shown in Table 3 , litter extracts from different treatments all exhibited inhibitory effects on lettuce seeds. At the same invasion degree, N5 treatment increased the inhibitory intensity of litter extracts compared to N0 treatment, with the inhibition degree increasing by 27% at S2A2. N12 treatment alleviated the inhibitory effect of litter extracts when only *S. canadensis* was present (S1 and S3) but had no significant effect on other invasion degrees. The difference in inhibition between N5 and N12 treatments indicated that appropriate nitrogen addition could effectively enhance the comprehensive allelopathic effect of *S. canadensis*.

At the same nitrogen addition level, different invasion degrees also significantly affected the allelopathic effect of extracts. In treatments with native *A. argyi* competition (S1A3, S2A2, and S3A1), the allelopathic effect of extracts significantly decreased as the proportion of *S. canadensis* increased across all three nitrogen treatments. This suggested that mixed planting of *A. argyi* with *S. canadensis* influenced the allelopathic effect of *S. canadensis*.

Two-way ANOVA results showed that *S. canadensis* litter significantly affected lettuce seeds under both nitrogen deposition and invasion degree treatments. Under combined treatment, the synthetical allelopathic index of litter was slightly reduced but still significantly affected (Table 2).

2.3 Effects of Nitrogen Addition and Invasion Degree on Total Phenol and Flavonoid Contents in Litter

Both nitrogen addition and invasion degree treatments alone significantly affected allelochemical content in *S. canadensis* litter. Under combined treatment, they still significantly affected total phenol content but had no significant effect on total flavonoids (Table 2). As shown in Table 3, at the same invasion degree, total phenol content in *S. canadensis* litter increased under N5 treatment but decreased under N12 treatment compared to N0 treatment. Under nitrogen-added soil and the same nitrogen addition level, litter total phenol content decreased as competition from native *A. argyi* decreased. The highest litter total phenol content occurred under N5 treatment at S1A3, increasing by 140% compared to N0 treatment at S1A3. The lowest litter total phenol content occurred under N12 treatment at S3A1, decreasing by 33% compared to N0 treatment at S3A1.

For total flavonoids, *S. canadensis* litter showed the same trend as total phenols. The highest litter total flavonoid content occurred under N5 treatment at S1A3, increasing by 50% compared to N0 treatment at S1A3. The lowest litter total flavonoid content occurred under N12 treatment at S3A1, decreasing by 51% compared to N0 treatment at S3A1. Differences in allelochemicals suggested that nitrogen treatments and different invasion degrees might affect litter allelopathy by influencing allelochemical content in *S. canadensis* litter.

3 Discussion and Conclusion

Studies have shown that plant litter releases allelochemicals into the soil environment through leaching, volatilization, and decomposition. These allelochemicals alter microscopic structures such as cell division, elongation, and membrane permeability, interfering with seedling energy metabolism, mineral absorption, and photosynthesis (Kansoh et al., 2009), thereby affecting germination and growth of other plants (Mei et al., 2005; Sun et al., 2006). In this study, lettuce seeds were inhibited by *S. canadensis* aqueous extracts during germination and growth, with different plant parts showing varying sensitivity to allelochemicals in the extracts. Compared to plant height, leaf length, and leaf width, litter extracts showed more significant inhibition on root length growth. This may be because plant radicles are the first to contact allelochemicals during seedling growth, making them more vulnerable to influence (Turk & Tawaha, 2003). Inhibition of root length reduces nutrient absorption capacity, thereby suppressing plant growth. Additionally, significant inhibition of lettuce seedling leaf length may hinder photosynthetic rates during seedling growth, preventing rapid accumulation of organic matter (Huang et al., 2013) and ultimately affecting competitive ability in the community, which benefits *S. canadensis* invasion. These results indicate that *S. canadensis* litter possesses strong allelopathic effects that significantly inhibit lettuce germination and growth, with lettuce roots being most sensitive to allelopathic inhibition.

Total phenols and flavonoids are important allelochemicals in invasive plants, and their content significantly affects plant allelopathy. In natural environments, they can not only directly inhibit growth of other native plants but also strongly influence soil biota activities. For example, 8-hydroxyquinoline from roots of diffuse knapweed (*Centaurea diffusa*) has antimicrobial activity in soil (Vivanco et al., 2004). Polyphenols are known for their defense against herbivores and pathogens, acting directly as oviposition stimulants, attractants, or deterrents to protect plants from insect damage. For instance, total phenols released into soil by the invasive plant *Chromolaene odorata* can inhibit growth of local soil pathogens (Mangla et al., 2008). Allelochemical content in litter is influenced by various factors including plant growth cycle, selective pressure, and competition from other species. Some studies have found that allelochemical release varies with nitrogen deposition. Increased nitrogen deposition enhances allelochemical release in *Schima superba* Gardn. and *Pinus massoniana* (Xiao, 2009), and the allelopathic effect of *Ipomoea cairica* litter is effectively enhanced at medium and high nitrogen levels (Chen et al., 2016). In this study, at the same invasion degree, low nitrogen deposition (N5) treatment significantly increased allelopathic effects compared to no nitrogen (N0) or high nitrogen deposition (N12) treatments, with allelochemicals in litter showing the same trend. The possible reason is that allelochemical production depends not only on organism physiological characteristics but also on external nutrient conditions. Under resource-poor conditions (no nitrogen addition), niche competition is intense, and *S. canadensis* must first meet underground root growth demands to acquire more nutritional resources (Luo et al., 2014). Tu et al. (2013) found similar phenomena in *Flaveria bidentis*, where invasive species effectively increased growth rates in low-nitrogen habitats to maintain competitive advantages. In contrast, N5 treatment significantly increased allelochemicals in litter, possibly because nitrogen deposition increased nitrogen availability, reducing allocation to underground biomass while increasing aboveground biomass during *S. canadensis* growth (Kansoh et al., 2009; Hess et al., 2018). Simultaneously, increased allelochemical content in litter was needed to inhibit other native species and facilitate its own survival and expansion. Allelochemicals under N12 treatment were significantly lower than under N5 treatment, possibly because under nutrient-rich conditions (high nitrogen addition), *S. canadensis* growth was no longer nitrogen-limited (Luo et al., 2014), interspecific resource competition weakened, reducing allocation to allelochemical content in litter for safe coexistence. Additionally, Yang et al. (2018) found that nitrogen fertilization effectively extended leaf lifespan and significantly increased ramet production in *S. canadensis*, greatly promoting its clonal reproduction and enhancing community competitiveness (Yang et al., 2018). This may represent an important growth strategy for invasive plants. In summary, this study answers the first scientific question: nitrogen deposition enhances the allelopathic effect of invasive plants on native plants.

In addition to nitrogen deposition, the presence of native competing species also significantly affects allelochemical content in litter. Increasing evidence shows that plants can chemically recognize neighboring plants and regulate synthesis and release of corresponding allelochemicals to inhibit them, a phenomenon known as plant chemical recognition communication (Pettersson et al., 2008; Li et al., 2016). Kong et al. (2016) found that wheat secretes allelochemicals to inhibit surrounding weed growth when weeds are present. As the number of neighboring plants increases (intensified interspecific competition), the amount of allelochemicals released by plants also increases. Similar to previous studies, this study found that under the same nitrogen addition treatment, allelochemical content in *S. canadensis* litter at the initial invasion stage (S1A3) was significantly higher than at the late invasion stage (S3A1), indicating that interspecific competition intensity (invasion degree) significantly affected allelochemical content in *S. canadensis*, while no difference in allelopathic effects between S1 and S3 suggested that intraspecific competition did not affect allelochemical release in *S. canadensis*. These results confirm the second scientific question: different competition levels (interspecific competition) affect litter allelopathy.

Two-way ANOVA showed that both nitrogen deposition and invasion degree significantly affected total flavonoid content in litter, but their interaction had no significant effect on total flavonoid content. This may explain why nitrogen addition and different invasion degrees significantly affected allelopathy of *S. canadensis*, but the interaction slightly reduced the effect on the synthetical allelopathic index of litter. These results indicate that nitrogen deposition and competition level interact to affect litter allelopathy. However, the specific internal mechanisms by which nitrogen deposition regulates allelopathic effect intensity require further research.

In conclusion, this study demonstrates that *S. canadensis* litter has strong allelopathic inhibitory effects on tested native plants, which may benefit its successful invasion. Meanwhile, as nitrogen deposition and invasion processes (interspecific or intraspecific competition intensity) change, allelochemical content allocation in *S. canadensis* litter also changes, resulting in different allelopathic effects that affect its invasiveness and potentially intensify invasion. These findings help enrich and develop understanding of allelopathic mechanisms in the invasive plant *S. canadensis*. However, considering current research on *S. canadensis* allelopathic mechanisms, allelopathy in *S. canadensis* is a comprehensive trait expressed through recipient plant responses to its allelochemicals, resulting from multiple factors and mechanisms. Future research should combine other influencing factors such as microorganisms and root exudates to deeply investigate nitrogen deposition effects on *S. canadensis* allelopathy. Finally, as nitrogen deposition is a gradual global change process, strengthening control of *S. canadensis* and ecological management of nitrogen deposition is becoming increasingly urgent under current environmental conditions.

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Note: Figure translations are in progress. See original paper for figures.