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REGULAR ARTICLE

Litter decomposition rate and nutrient dynamics of giant ragweed (*Ambrosia trifida* L.) in the non-native habitat of South Korea

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Abstract
Aim Ambrosia trifida L. is designated as an invasive exotic plants in South Korea. Despite its widespread distribution in South Korea, research on *A. trifida* is limited. Organic matter input by *A. trifida* litter decomposition is predicted to change the soil environment. In this study, we investigated the effects of *A. trifida* litter decomposition on soil nutrient status.
Methods We used the litterbag method to investigate the decomposition rate, decay constant (k), carbon/nitrogen (C/N) ratio, and nutrient dynamics of *A. trifida* litter during decomposition.
Results The decay constants (k) of leaf, stem, and root litter after 11 months of decomposition were 1.93, 1.47, and 1.28, respectively. After 22 months of decomposition, the decay constants (k) of leaf, stem, and root litter were 1.01, 0.99 and 1.84, respectively. After 22 months, approximately 85% of organic matter, 79% of nitrogen (N), 98% of phosphorus (P), 96% of potassium (K), 96% of magnesium (Mg), and 69% of calcium (Ca) were returned to the soil.
Conclusion Our results provide key insights into the nutrients exchange between *A. trifida* and soil. Given the biological characteristics of *A. trifida*, the input of a large amount of organic matter to the soil and the nutrients released through the decomposition of this organic matter are expected to enhance the growth and nutrient absorption of *A. trifida* in invaded areas.

Keywords Invasive alien species · *Ambrosia trifida* · Decomposition rate · Mineralization · Nutrient dynamics · Plant-soil feedback

Introduction

Invasive plants have become one of the main factors that threaten the global ecosystem and cause economic problems (Early et al. 2016; Pimentel et al. 2005; Vitousek et al. 1997). Several studies have been conducted to understand the characteristics of invasive plant species (Balogh et al. 2003; Williams et al. 2018; Williamson and Fitter 1996) and the factors responsible for their successful invasion (Cadotte et al. 2009; Dukes and Mooney 1999) with various possible theories (Davis et al. 2000; Keane and Crawley 2002; Maron and Vilà 2001; Simberloff and Von Holle 1999; Tilman 1980). Many studies have reported the impacts of plant invasion on the ecosystem structure (Damasceno et al. 2018; Gaertner et al. 2014), ecological processes (Davies 2011; Gaertner et al. 2014), species diversity (Davies 2011; Meier and Bowman 2008), and nutrient cycling (Ehrenfeld 2003; Jo et al. 2017). Plants are considered as a link between above- and belowground environments because they uptake nutrients from the soil and return energy to the soil in the form of litter. Litter is defined as dead organic matter comprising plant organs such as leaves, stems, and flowers that have fallen on the ground

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and roots in the ground (Berg 2006). Plant litter exerts effects both directly and indirectly on the ecosystem (Facelli 1994; Freschet et al. 2013; Moore et al. 2004; Olson and Wallander 2002; Xiong and Nilsson 1999). Litter decomposition affects soil organic matter accumulation and carbon balance in terrestrial ecosystems (Austin and Ballaré 2010; Zhang et al. 2014). Decomposed litter constitutes soil organic matter; thus, adding organic matter into the soil directly influences on the soil environment (Berg 2000; Cotrufo et al. 2015; Medina-Villar et al. 2015; Plaster 2013). Soil moisture level, fertility (Jia et al. 2018; Xiong et al. 2008), and pH are also influenced by litter input (Xu et al. 2006), and rapid decomposition of nutrient-rich litter can replenish soil nutrients (Veen et al. 2019). Also, litter indirectly modifies the ecosystem by affecting soil organisms and plant communities (Carson and Peterson 1990). Accumulated litter may disrupt seedling emergence and growth during the seedling stage (Facelli and Pickett 1991), and soil properties can be modified by changes in nutrient dynamics, which are driven by the dominant plant species (Heneghan et al. 2006). Because plant characteristics differ, the effects of litter can be either negative or positive depending on the plant species (Wardle et al. 2004). Invasive species tend to have more positive effects on soil than native species. Changes in soil moisture and increased litter production can enhance environmental conditions (Farrer and Goldberg 2009; Wolkovich et al. 2009), and nutrient-rich litter input can modify soil microbial groups composition and nutrient cycling, which generates positive feedbacks that increase plant invasion (Zhang et al. 2019). On the other hand, Olson and Wallander (2002) reported that exotic invasive forb litter inhibits the seedling growth of native species, and Asplund et al. (2018) suggested that interactions between litter type and habitat type can have an indirect negative effect on plant growth. Invasive exotic plant species possess unique traits such as high litter quality or quantity (Aerts 1997; Chen et al. 2018) and rapid growth or high biomass (Abul-Fatih et al. 1979b; Smith et al. 2000). Moreover, the litter of invasive plants tends to decompose faster than that of native species; thus litter decomposition of invasive plant species tends to have a greater impact on the physical and chemical properties of soil by altering the ecological process (Allison and Vitousek 2004; Hobbie 2015). Both native and invasive plant species influence the ecosystem, but invasive plants tend to benefit more from litter than native species (Dickson et al. 2012).

Ambrosia trifida L., commonly known as giant ragweed, originated in North America and was first documented in South Korea in 1964 (Lee et al. 2010). *Ambrosia trifida* L. is a dicotyledonous annual plant species that grow to more than 4 m in height and inhabits a wide range of habitats including disturbed ground, riversides, agricultural land, and abandoned areas. *Ambrosia trifida* L. is one of the most problematic weeds in its native area because of its rapid growth, high biomass, and high seed mass per plant (Abul-Fatih et al. 1979a; Montagnani et al. 2017). These ecological traits, especially rapid growth and high biomass, are advantageous for *A. trifida* because these traits enable it to dominate the invaded areas in a short period by suppressing the growth of other plant species (Theodore et al. 1994). Thus, *A. trifida* invaded areas exhibit low species diversity and poor biomass compared with uninvaded areas (Barnett and Steckel 2013; Johnson et al. 2007). Since *A. trifida* causes many problems, it has been designated as one of the most harmful invasive alien plant species in South Korea. Many studies have been conducted on *A. trifida* in South Korea. However, most of these studies focused on the distribution (Choi et al. 2007; Kil et al. 2004; Kim 2017; Park et al. 2017), the decline in biodiversity (Kim et al. 2018), and the development of management practices (Kang et al. 1998; Lee et al. 2010; Lee et al. 2007), but research on the soil environment after invasion has been limited. Understanding the post-invasion effects of *A. trifida* on the soil environment may be crucial because this information would help to develop a management strategy and restoration plan for the invaded areas (D'Antonio and Meyerson 2002).

In the field, litter is decomposed in a mixed form because a plant community usually comprises various species. However, in this study, we conducted single-species litter decomposition because *A. trifida* generally forms a simple and dense monoculture in invaded areas. Since *A. trifida* is an annual plant species, its litter (especially leaf litter) disappears within a year. However, in the fields, stems of *A. trifida* remain as standing litter for a relatively long period of time. Therefore, we conducted a 2-year experiment to investigate the leaf, stem, and root litter decomposition and nutrient dynamics of *A. trifida*. We hypothesized that *A. trifida* litter has a significant impact on the soil environment because of the greater biomass and nutrient input through rapid decomposition. We also hypothesized that litter decomposition of *A. trifida* modifies the habitat to make it more suitable for the growth of *A.trifida*. To test this hypothesis, we conducted a litterbag experiment from November 2016 to September 2018. We aimed to better understand the decay rates and nutrient release patterns of each organ of *A. trifida* during decomposition. Our specific objective was to determine the contribution of *A. trifida* litter decomposition to the soil nutrient status in invaded areas.

Materials and methods

Study area

This study was conducted in the western part of the Civilian Control Zone (CCZ) in Paju, Gyeonggi-do, South Korea (Fig. 1). Land use in the CCZ is highly restricted for security reasons; therefore, only authorized areas could be used for the experiment. Unlike other parts of the CCZ, western CCZ is close to Seoul, the capital city of South Korea, and access to the CCZ in the western part is relatively high. Additionally, because farmland has been developed over a wide range, the western part of the CCZ has more frequent disturbance than other parts (Park and Nam 2013). The percentage of non-native plants, including invasive alien plants, is relatively high in western CCZ, and *A. trifida* shows widespread distribution with rapid progression around the reclaimed area in this region (Kim and Kang 2019; Lee et al. 2016). This area was selected for the experimental site because western CCZ contains a wide range of *A. trifida* habitats and presents a relatively low risk of plant removal. The study site is located in an abandoned area (37°54′ 58.42“N, 126°46’ 32.69”E), near the Imjin River where was formerly farmland but not currently used. The soil of the study site was a silt loam with an average soil pH of 6.47 and soil C/N ratio was 10.9 (2.84% C and 0.26% N). The Paju meteorological observatory station is located 4 km distance away from the study site. Over a period of 10 years (2008–2017), the mean annual temperature and precipitation at the meteorological station were 11.01 °C and 1295.44 mm, respectively. Over the study period (2016–2018), the mean annual temperature and precipitation were 10.6 °C and 978.65 mm, respectively (Fig. 2).

Litterbag experiment

The litterbag method was used to investigate the decomposition rate of *A. trifida* litter and to monitor litter nutrient dynamics. The litterbag method is one of the most common methods used to determine the dynamics of chemical elements and organic compounds during plant decomposition. Thus, by using this simple method, important data about the ecosystem process can be obtained (Berg 2006). After the growing season, senescent aboveground parts of *A. trifida* were harvested from the vicinity of the study area in October 2016, and leaves and stems were separated. Roots were excavated from the soil using a shovel and gently rinsed with tap water to remove the adhering soil particles. All collected samples were dried in an oven at 50 °C for 72 h, and a batch of three samples of each weighted litter type (leaf, stem, and root) was reserved to analyze initial carbon and nutrients contents. Litterbags (ca. 20 cm × 25 cm) were prepared from 1 mm mesh nylon fabric. Approximately 5 g each of leaf, stem, and root litter were packed separately in litterbags and labeled using a numbered aluminum tag with the exact litter weight. Leaf and stem litterbags (60 each) were tied up by string, and then anchored on the ground, and sixty root litterbags were buried in the soil at a depth of 20 cm in November 2016. Leaf, stem, and root litterbags (3 each) were retrieved after 1 month (December 2016) and then leaf, stem, and root litterbags (3 each) were retrieved every 2 months interval from February 2017 to September 2018. Debris, mineral soil, and roots that intruded the litterbags from the outside were removed manually in the laboratory. Each litterbag was oven dried at 50 °C for 72 h and then weighted. After weighing, litter samples were ground using a mixer and preserved in plastic bags for chemical analysis. The weight of the remaining litter was expressed as a percentage against the initial dry weight after a given time, and calculated using the following equation (Petersen and Cummins 1974)

$$Weight\ remaining\ (\%) = \frac{W_t}{W_0} \times 100$$

where W_0 represents the initial dry weight of litter, and W_t represents the dry weight of litter at time *t*.

The litter decay constant (*k*) of each litter type was calculated using Olson's formula (Olson 1963)

$$X_t = X_{0e}{}^{-kt}$$

where X_0 is the initial dry weight of litter, X_t is the

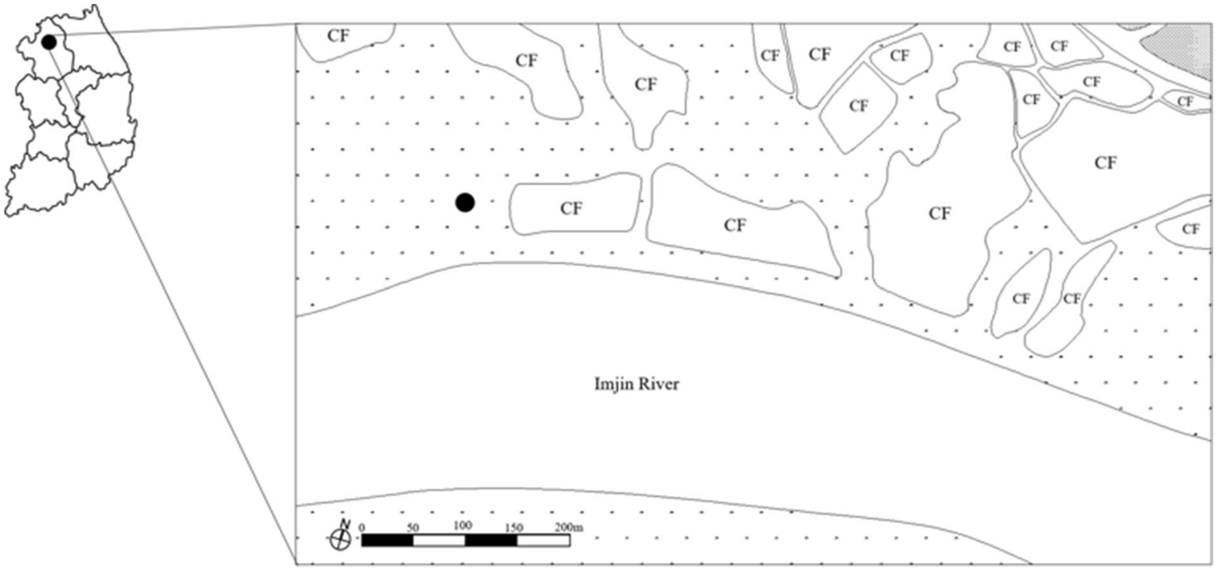

Fig. 1 Location of the study site in Paju, Gyeonggi-do, South Korea. Black circle (•) indicates the litterbag experiment site (37°54′58.42" N, 126°46'32.69" E) in the Civilian Control Zone (CCZ). Dotted areas indicate areas invaded by *A. trifida*. CF, crop field

remaining dry weight of litter at time t, t is the time (year), and k is the decay constant.

Chemical analysis

Chemical analysis of retrieved litter was conducted. The organic C contents of initial and decomposing litter were analyzed using an Elemental Analyzer (Flash EA 1112, Thermo Electron Co., USA). Total nitrogen (TN) content of the litter was analyzed using the Kjeldahl method, and total phosphorus (TP) content was analyzed using an inductively coupled plasma atomic emission spectrometer (ICP-730ES, VARIAN, Australia) after digestion in a mixture of potassium sulfate, copper sulfate and sulfuric acid in a block digester. The contents of potassium (K), magnesium (Mg) and calcium (Ca) in the litter were analyzed using an ICP atomic emission spectrometer (ICP-730ES, VARIAN, Australia) after digestion in a mixture of 60% of nitric acid and 70% of perchloric acid in a block digester. The percentage of a nutrients remaining in the decomposing litter after a certain period of time was calculated using the following

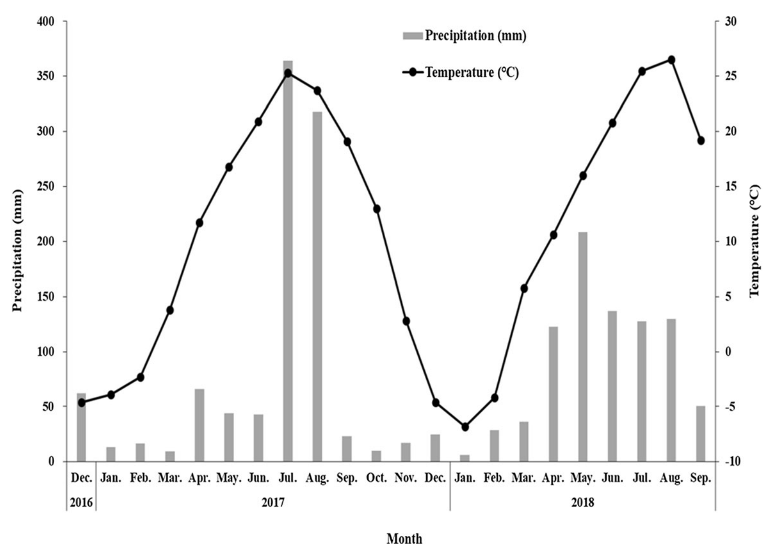

Fig. 2 Mean monthly precipitation and temperature at the Paju meteorological station during the study period (December 2016–September 2018)

equation (Alhamd et al. 2004):

$$Remaining\ (\%) = \frac{L_t C_t}{L_0 C_0} \times 100$$

where L_t represents the dry weight of litter at time t, L_0 represents the initial dry weight of litter, C_t is the nutrient concentration in the litter at time t, and C_0 represents the initial nutrient concentration in litter.

Statistical analysis

All statistical analyses were carried out using the R program (R CoreTeam 2016). The effects of litter type and seasonal variation on litter remaining weight were examined with the one-way analysis of variance (ANOVA), and the statistical significance of differences between means was determined using a post-hoc Tukey test at $P < 0.05$. Differences in the decay constant (k) were examined using the Kruskal-Wallis test and Dunn's test was performed to compare means at $P < 0.05$. To determine the effects of litter type on nutrient concentration (N, P, K, Mg, and Ca) in the decomposing litter after a certain period of time, nutrient concentration data were log-transformed to improve normality. N concentration was analyzed using the Welch's ANOVA followed by Games-Howell post-hoc test to compare means at $P < 0.05$. P concentration was examined using one-way analysis of variance (ANOVA) followed by a post-hoc Tukey test. K, Mg, and Ca concentrations were analyzed using the Kruskal-Wallis test, and the statistical significance of differences between means was determined using a Dunn's test at $P < 0.05$.

Results

Litter decomposition rate

The decomposition of leaf, stem, and root litter of *A. trifida* steadily continued over the study period (Fig. 3). After the 11 months of decomposition, the remaining weights of leaf and stem litter were approximately 17.1% and 30.4%, respectively; however, the remaining weight of root litter was approximately 34.7%. At 22 months, the remaining weights of leaf, stem, and root litter showed significant differences at 11.0%, 16.5%, and 3.5%, respectively. Leaf litter decomposed much faster than stem and root litter until 16 months; however, root litter decomposed more rapidly than other litter types thereafter. Litter anchored on the ground, especially leaf litter, decomposed faster than root litter which buried under the soil until 11 months; however, after 16 months, the remaining weight of root litter decreased sharply compared with that of leaf and stem litter. Seasonal variation in climate had a significant effect on litter remaining weight ($p < 0.05$). The decay constant (k) of each litter type showed significant variation ($p < 0.05$; Table 1). After 11 months, litter decay rates decreased in the following order: leaf > stem > root. However, at 22 months, the order of litter decay rates changed to leaf > root > stem. The decay constants (k) of leaf and stem litter continued to increase over time, and reached the highest level at 11 months. After 11 months, whereas the decay constant of root litter continued to increase, the decay constants (k) of leaf and stem litter gradually declined.

C/N ratio

The initial organic C contents of leaf, stem, and root litter of *A. trifida* were 40.6%, 42.8% and 45.3%, respectively (Fig. 4). The amount of organic C in all litter types decreased gradually during decomposition. After 22 months, the organic C contents of leaf, stem and root litter were 30.5%, 38.7% and 28.3%, respectively (Fig. 4). Figure 5 shows seasonal changes in the C/N ratio of *A. trifida* litter during decomposition. The initial C/N ratios of leaf, stem, and root litter were 12.7, 136.3, and

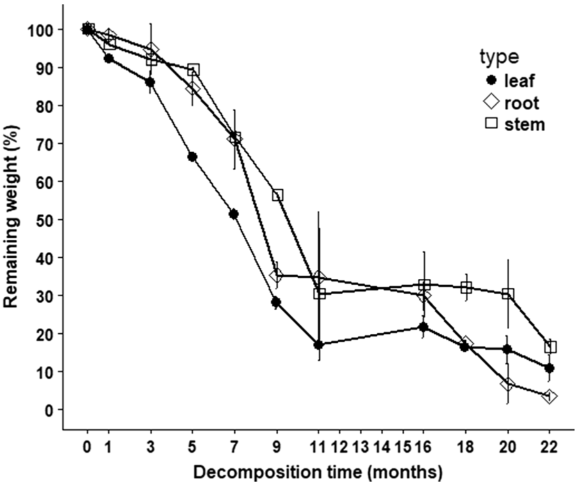

Fig. 3 Remaining weights (%) of decomposing leaf, stem and root litter of *Ambrosia trifida* during the experimental period at the study site. Data represent means ± SD ($n = 3$)

Table 1 Decay constants (k) of leaf, stem, and root litter after 11 and 22 months of decomposition (Data are means ± SD; $n = 3$)

Litter type	Decay constants (k)	
	11 months	22 months
Leaf	1.93 ± 0.08 ^{a*}	1.01 ± 0.20 ^{a}
Stem	1.47 ± 0.82 ^{b}	0.99 ± 0.06 ^{b*}
Root	1.28 ± 0.70 ^{b}	1.84 ± 0.17 ^{a}

Different letters within the k column indicate significantly different means ($^{*}p < 0.05$, Tukey's test)

452, respectively. The C/N ratio of root litter decreased rapidly during decomposition; however, that of stem litter increased sharply to 321 after 1 month and decreased thereafter. The C/N ratio was the lowest in leaf litter and the highest in root litter during decomposition. After 22 months, C/N ratios of leaf, stem, and root litter of *A. trifida* were 12.5, 38.5 and 38.3, respectively.

Changes in nutrients concentration and percentage of nutrient remaining during litter decomposition

N and P

Figure 6 shows the dynamics of N and P in *A. trifida* leaf, stem, and root litter, and the percentages of N and P remaining during decomposition. The initial concentrations of N in leaf, stem, and root litter were 30.68 mg/g, 6.31 mg/g, and 7.02 mg/g, respectively. The initial N concentration was significantly higher in the leaf litter than in stem and root litter ($p < 0.01$). The N

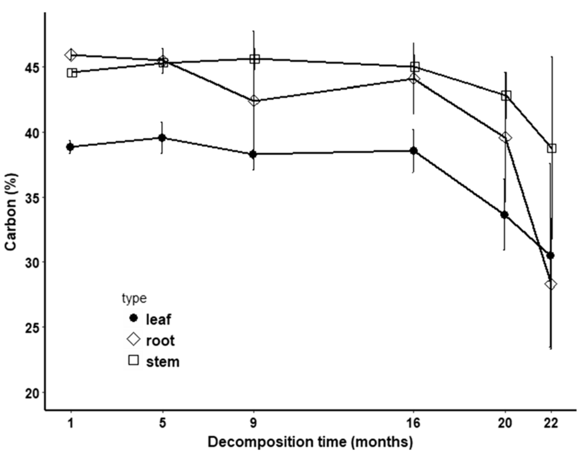

Fig. 4 Changes in organic C (%) of *Ambrosia trifida* leaf, stem, and root litter of during the experimental period. Data represent means ± SD ($n = 3$)

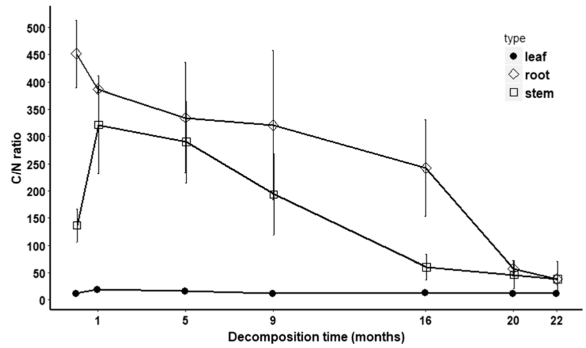

Fig. 5 Changes in the C/N ratio of decomposing leaf, stem, and root litter of *Ambrosia trifida* during the experimental period. Data represent means ± SD ($n = 3$)

concentration of decomposing leaf litter decreased to 19.6 mg/g after 1 month and then increased continuously until 11 months followed by a decline thereafter. The N concentrations of decomposing stem and root litter decreased to 3.17 mg/g and 2.14 mg/g, respectively, after 1 month, and increased gradually thereafter (Fig. 6a). Percentages of N remaining in decomposing leaf, stem, and root litter decreased sharply after 1 month to 59.0%, 48.1%, and 33.8%, respectively, and then continued to decrease gradually (Fig. 6b). At the end of the experiment (22 months), percentages of N remaining in the leaf, stem, and root litter were 6.3%, 38.3%, and 4.2%, respectively, and percentages of N remaining in the root and leaf litter were significantly lower than that remaining in the stem litter ($p < 0.01$). The N immobilization period was not detected during *A. trifida* litter decomposition (Fig. 6b). The initial P concentrations of leaf, stem, and root litter were 11.0 mg/g, 3.4 mg/g, and 0.9 mg/g, respectively. The P concentration of leaf litter decreased rapidly to 2.6 mg/g after 1 month and then increased to 4.5 mg/g until 7 months. The P concentration of stem litter showed a declining trend from the beginning of the experiment until 5 months (1.1 mg/g) and increased slightly thereafter (Fig. 6c). Compared with leaf litter, the P concentration of stem and root litter showed less variability during decomposition. The P concentration of root litter showed an increasing trend until 11 months, and decreased thereafter. At 22 months, the P concentrations of leaf, stem, and root litter were 1.54 mg/g, 1.50 mg/g, and 0.82 mg/g, respectively. Similar to N, the P concentration of leaf litter was also higher than that of stem and root litter during decomposition (Fig. 6c; $p < 0.01$). Percentage of P remaining in leaf litter decreased rapidly to 22.0% after 1 month, and then decreased gradually until

22 months (Fig. 6d). The percentage of P remaining in stem litter showed a similar trend to that remaining in leaf litter. No P immobilization period was observed during the decomposition of the leaf and stem litter. Unlike aboveground litter, the percentage of P remaining in root litter increased to 145.3% after 3 months and then decreased rapidly. In roots, P was immobilized until the first 5 months and mineralized thereafter. At the end of the experiment (22 months), percentages of P remaining in the leaf and root litter was significantly lower than that remaining in the stem litter ($p < 0.05$).

K, mg and Ca

Figure 7 shows the dynamics of K, Mg and Ca in *A. trifida* leaf, stem, and root litter and the percentage of each nutrient remaining during decomposition. The initial concentrations of K in leaf, stem, and root litter were 64.1 mg/g, 34.6 mg/g, and 3.1 mg/g, respectively (Fig. 7a). The concentration of K in leaf and stem litter decreased rapidly during the early stage of decomposition but showed no fluctuation after 9 months. By contrast, the concentration of K in root litter increased to 5.6 mg/g after 5 months and then declined continuously. By the end of the experiment (22 months), the K concentrations of leaf, stem, and root litter were 5.0 mg/g, 2.6 mg/g, and 1.5 mg/g, respectively. Overall, the K concentration of all litter types decreased at the beginning of the experiment; however, only the declining pattern of leaf litter was significantly different from that of stem and root ($p = 0.04$). The percentages of K remaining in leaf and stem litter decreased rapidly until 9 months but showed no variation thereafter (Fig. 7b). K immobilization was not detected in leaf and stem litter during decomposition. The percentage of K remaining in root litter increased to 153.7% (i.e., immobilization) until 5 months, and then mineralized until the end of the experimental period. After 22 months, the percentages of K remaining in leaf, stem, and root litter were 0.8%, 1.2% and 1.8%, respectively. The percentage of K remaining in leaf litter was significantly different from that of stem and root ($p < 0.05$). The initial concentrations of Mg in leaf, stem, and root litter were 23.3 mg/g, 2.18 mg/g, and 1.0 mg/g, respectively (Fig. 7c). Initial Mg concentration of leaf was significantly higher than those of stem and root litter ($p < 0.01$). Mg concentration of leaf litter decreased rapidly to 9.4 mg/g after 1 month and then gradually until 22 months. Mg concentrations of stem and root litter did not show large fluctuations during decomposition. During the decomposition, the Mg concentration of leaf litter was higher than the stem and root litters. After 22 months, the Mg concentrations of leaf, stem, and root litter were 5.31 mg/g, 2.1 mg/g, and 5.64 mg/g, respectively. The percentages of Mg remaining in leaf and stem litter decreased rapidly to 37.1% and 68.7%, respectively, after 1 month and then decreased gradually (Fig. 7d). The percentage of Mg remaining in root litter first decreased to 73.9% after 1 month, increased to 111.3% after 7 months, and then decreased rapidly until 22 months. During decomposition, Mg was released continuously from leaf and stem litter; however, in root litter, Mg was immobilized after 5 months and then released again (Fig. 7d). After 22 months, the percentages of Mg remaining in leaf, stem, and root litter were 2.5%, 15.9% and 19.2%, respectively. The percentage of Mg remaining of leaf litter was significantly lower than that stem and root litters ($p < 0.01$). The initial Ca concentration of leaf, stem, and root litter were 87.7 mg/g, 12.0 mg/g, and 4.7 mg/g, respectively (Fig. 7e). The Ca concentration of leaf litter was consistently significantly higher than that of stem and root litter ($p < 0.01$). In leaf litter, Ca concentration decreased to 48.2 mg/g after 1 month, and increased gradually to 72.1 mg/g until 9 months, and then decreased thereafter. By contrast, the Ca concentration of stem and root litter showed no significant variation during decomposition. After 22 months, the Ca concentration of leaf, stem, and root litter were 45.3 mg/g, 19.3 mg/g, and 8.6 mg/g, respectively. The percentage of Ca remaining in leaf and stem litter decreased rapidly to 2.7% and 16.3%, respectively, after 1 month (Fig. 7f). The percentage of Ca remaining in root litter decreased to 69.6% after 3 months, and increased to 112.6% until 7 months, and then decreased rapidly thereafter. During decomposition, Ca was released continuously from leaf and stem litter. However, in root litter, Ca was immobilized at 7 months, and mineralized again thereafter. After 22 months, the percentages of Ca remaining in leaf, stem, and root litter were 0.2%, 2.1% and 6.6%, respectively. Both Ca concentration and percentage of Ca remaining showed significant differences between aboveground and belowground litter ($p < 0.01$).

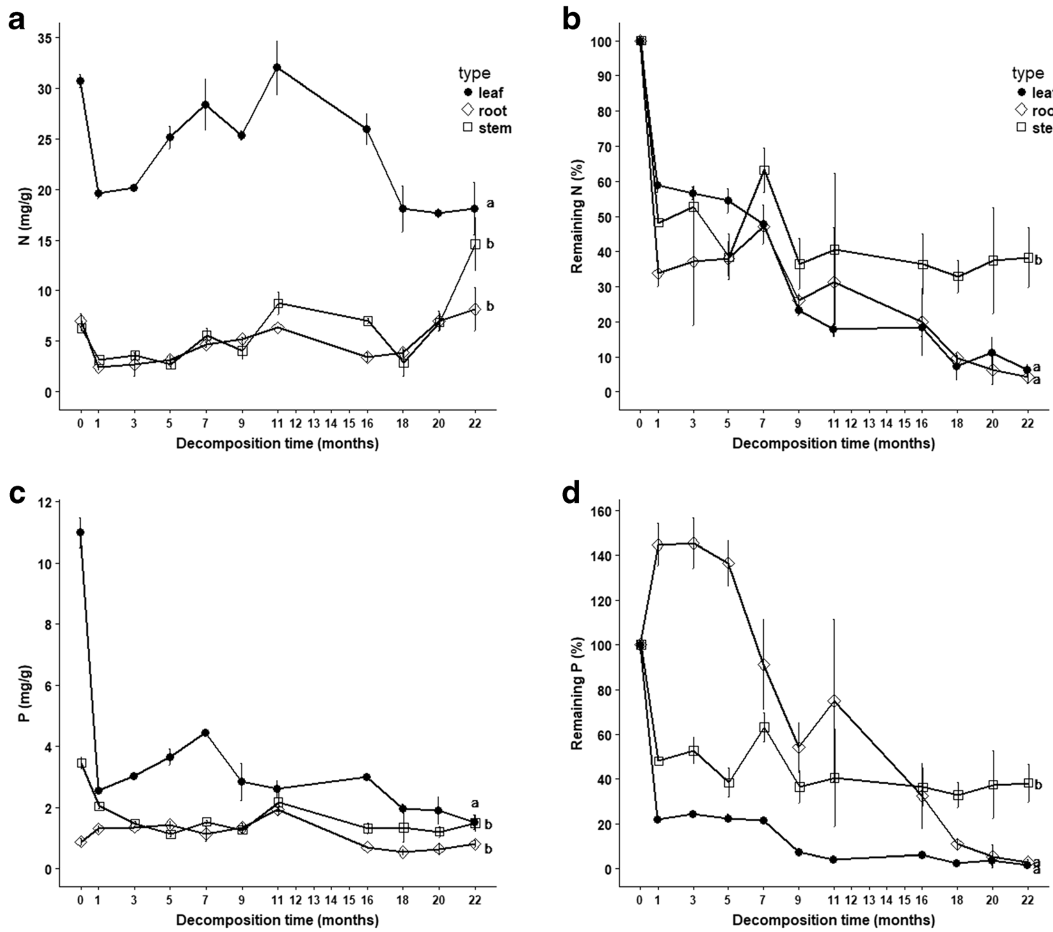

Fig. 6 The dynamics of N and P (**a**, **c**) and percentages of remaining N and P (**b**, **d**) of decomposing leaf, stem and root litter of *Ambrosia trifida* in the study area. Data represent means ± SD ($n = 3$)

Discussion

Decomposition of *A. trifida* litter

Litter decomposition rates vary among ecosystems, depending on soil biota, substrate quality, macro- and microclimate, and ecosystem condition (Zhang et al. 2008). In this study, the decomposition rate of leaf litter was higher than those of stem and root at an early decomposition stage, whereas root litter was higher at a later decomposition stage (Fig. 3). The rapid decline in leaf litter weight observed in this study is consistent with previous studies (Wang et al. 2014; Xu and Hirata 2005). This might be because the N concentration and C/N ratio of leaf litter were much higher and lower, respectively, than those of stem and root litter (Fig. 5). Lu et al. (2016) also reported that *A. trifida* leaf litter decomposed faster than other co-occurring native species because of its high initial nitrogen concentration. In this study, we did not analyze the lignin or cellulose content; however, since the C/N ratio is one of the predictable factors affecting litter decomposition (Liu et al. 2018; Taylor et al. 1989), we evaluated the litter quality based on the initial N content and C/N ratio of each litter. Litter quality, characterized by nitrogen and lignin content or C/N ratio, affects the litter decomposition rate because of its influence on microbial activity (Aerts 1997; Gulis and Suberkropp 2003; Mfilinge et al. 2002; Twilley et al. 1997). Generally, the initial litter decomposition rate shows a positive correlation with the initial litter N content (Coûteaux et al. 1995; Melillo et al. 1982). Twilley et al. (1997) reported that the decomposition rate of mangrove leaf litter varies according to its N content. Another factor that affects litter decomposition rate is the physical condition of the litter (Freschet et al. 2012). Leaf litter is more fragile than

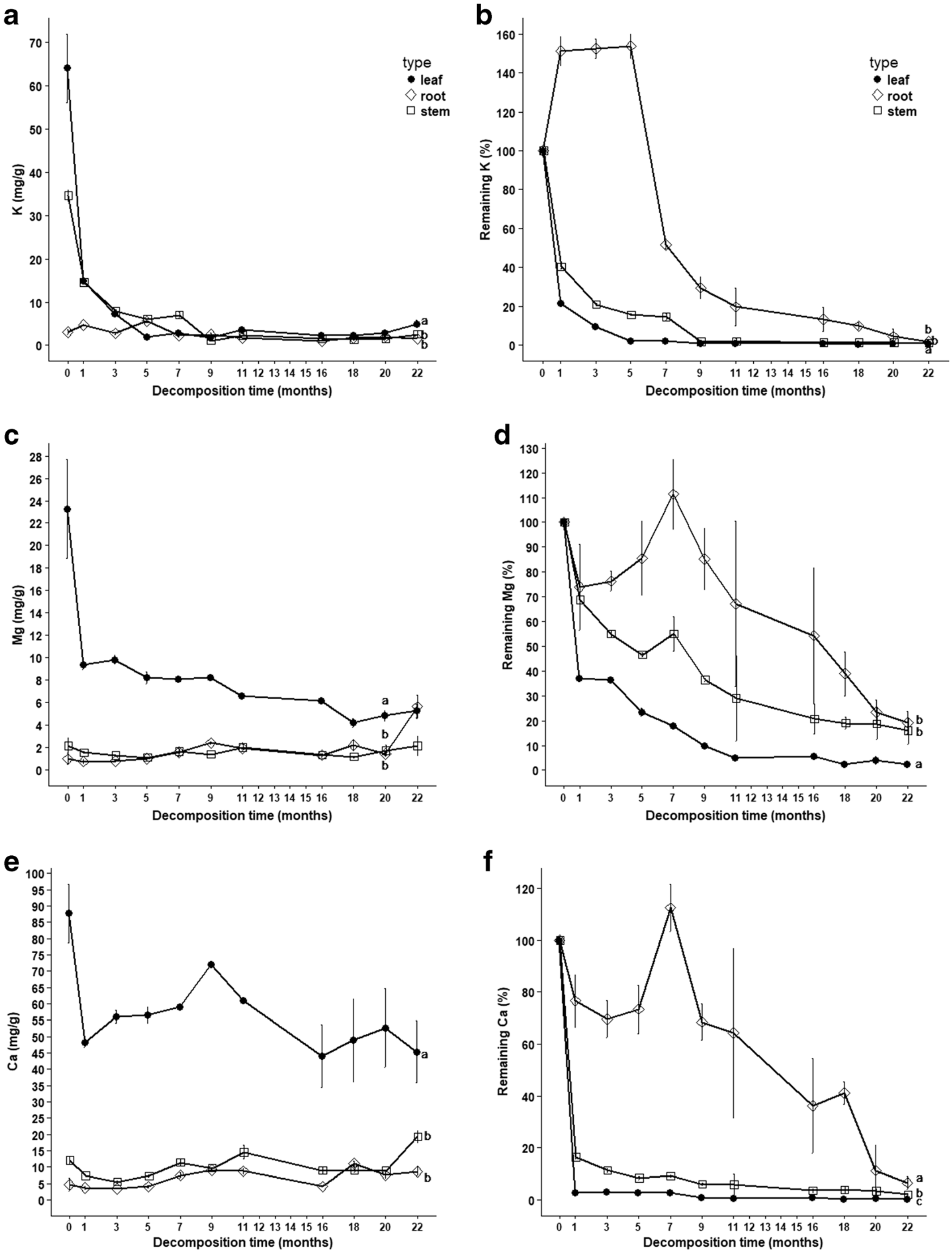

Fig. 7 The dynamics of K, Mg and Ca (**a**, **c**, **e**) and percentages of remaining K, Mg and Ca (**b**, **d**, **f**) in the decomposing leaf, stem, and root litter of *Ambrosia trifida* in the study area. Data represent means ± SD ($n = 3$)

stem and root litter. Like *A. trifida*, fast-growing exotic invasive plant species exhibit thinner leaves and low leaf construction costs (Baruch and Goldstein 1999; Wright et al. 2004); thus, leaves tend to decay faster than stems and roots. In this study, root decomposed more rapidly than stem litter at the later stage of decomposition (Fig. 3); this may be explained by climatic conditions and litter location. Climate is a major factor affecting the rate of litter decomposition (Aerts 1997; Djukic et al. 2018). Temperature and moisture conditions affect litter decay because of their effect on microbial activity and leaching (Bennett et al. 2011; González and Seastedt 2001; Swift et al. 1979). In the field, stem litter on the soil surface may be exposed to frequent dry conditions, unlike root litter buried in the soil (Jiang et al. 2016). Since precipitation in spring and winter is decreasing in South Korea (Jung et al. 2011), there is an increasing risk of drought, which could inhibit the decomposition of aboveground litter during the spring at a later decomposition stage. In our study, stem litter persisted longer than leaf litter. Also, in the field, some stem litters lasted as a standing litter where the *A. trifida* was abundant. The quality of stem litter and its decomposition were lower than that of leaf litter, but stem litter remained for a longer time on the ground. In this condition, stem litter may act as a barrier, indirectly affecting the *A. trifida* community because accumulated litter tends to promote increase in invasive plant biomass while negatively affecting seedling establishment and species diversity (Mariotte et al. 2017; Xiong and Nilsson 1999). Unlike aboveground litter (leaf, stem, and reproductive organs), roots usually remain in the soil. Thus, the decomposition of root could be affected either directly or indirectly by changes in soil conditions. Freezing and thawing could also alter the physical structure of the litter, as these phenomena increase nutrient leaching and microorganism accessibility, which facilitate litter decomposition at a later stage (Jiang et al. 2016; Ruhland et al. 2018; Taylor and Parkinson 1988). Additionally, root litter is more likely to interact with various soil microorganisms (e.g., bacteria and fungi), and soil invertebrates (e.g., millipedes), which have a positive impact on slowly decomposing litter (Hättenschwiler and Gasser 2005; Setälä and Huhta 1990).

Nutrient release during litter decomposition

The growth of terrestrial plants is highly dependent on litter decomposition rather than on the availability of mineral-rich soil for nutrient uptake, and organisms in the soil are ultimately responsible for ensuring the availability of nutrients for primary biomass production (Cotrufo et al. 2015; Moore et al. 2004; Wardle et al. 2004). Thus, primary production and decomposition are interdependent. Annual plants do not accumulate nutrients in plant biomass, but must return nutrients to the soil in an available form through litter decomposition for the next generation (Morris et al. 2016). In this study, although N concentration of each litter type fluctuated during decomposition, it increased steadily until 11 months (Fig. 6a). The increase in N concentration during litter decomposition has been reported previously (Berg and Staaf 1981; Xu et al. 2004), and is usually caused by the increase in microorganism activity (Hobbie et al. 2010; Langley and Hungate 2003; Xu and Hirata 2005). The dynamics of P in decomposing litter varies greatly among species (Baker et al. 2001; Enright and Ogden 1987; Gosz et al. 1973). In this study, P concentration showed a similar pattern to N (Fig. 6c). An increase in P concentration during litter decomposition has also been reported previously (Hobbie and Vitousek 2000; Moro and Domingo 2000). Since K is not a structural element, it tends to easily leach out from plant litter at the early stages of decomposition (Swift et al. 1979; Xu et al. 2004). In our study, K showed the highest mobility among all nutrients, which is consistent with a previous study (Wohler et al. 1975). Similar to K, Mg is also a non-structural element and therefore leaches out of litter at an early stage of decomposition (Osono and Takeda 2004). Thus, the dynamics of K and Mg showed a similar trend. Salamanca et al. (1998) reported similar dynamics of Mg. The increase in Mg concentration could be the result of nutrient translocation by fungal colonization at the later stages of decomposition (Bending and Read 1995). Most Ca in decomposing leaf and stem litter was released after 1 month, and Ca in decomposing root litter showed immobilization after 7 months (Fig. 7f). The pattern of Ca release in decomposing leaf and stem litter in this study was not supported by the previous studies; however, the pattern of Ca release from root litter was consistent with previous studies (Dziadowiec 1987), and its release could have been induced by fungal activity at the later decomposition stage. Overall, the mobility of nutrients was in the order K > Mg > Ca; the same order has been reported previously (Aponte et al. 2012; Osono and Takeda 2004; Rutigliano et al. 1998; Salamanca et al. 1998).

In this study, approximately 86% of organic matter, 79% of N, 98% of P, 96% of K and Mg, and 67% of Ca were returned to the soil environment after 22 months through decomposition. During 2017 and 2018, the average annual productions of *A. trifida* leaf, stem, and root litter at the study site were 1.45 kg/m^2, 7.43 kg/m^2 and 0.86 kg/m^2, respectively (Mun and Lee, *unpublished data*). This amount of biomass was converted to plant residues (litter) after the growing season, and incorporated into the soil through decomposition. In our study, the remaining weights of leaf, stem, and root litter after 22 months were 11.0%, 16.5% and 3.5%, respectively. During the decomposition period of 22 months, 1.29 kg/m^2 of leaf litter, 6.21 kg/m^2 of stem litter, and 0.83 kg/m^2 of root litter were incorporated into the soil as organic matter. Therefore, a total of 8.33 kg/m^2 litter was returned to the soil as organic matter after 22 months (Table 2). The total amounts of N, P, K, Mg, and Ca released from the litter into the soil through over 22 months were 76.49 g/m^2, 40.25 g/m^2, 349.02 g/m^2, 47.25 g/m^2, and 189.55 g/m^2, respectively. Previous studies have reported the relationship between soil nutrients concentration level and plant invasion processes (Pyšek et al. 2012; Sardans and Peñuelas 2012; Vilà et al. 2011), and Sardans et al. (2017) revealed that invasive plants were associated with soil nutrients levels such as N, P, and K availabilities. Soil properties in *A. trifida* invaded area were higher than those in adjacent uninvaded areas ($p < 0.05$). The soil organic matter (SOM), NO_3^-, total phosphorus (T-P), K, Mg, and Ca contents of *A. trifida* invaded soil were 10.9 ± 5.5%, 4.41 ± 1.27 μg/g, 3.2 ± 2.4 mg/g, 9.2 ± 3.3 mg/g, 9.1 ± 6.4 mg/g, and 67.0 ± 19.3 mg/g; on the other hand, soil property contents of uninvaded areas were 5.6 ± 1.8%, 3.2 ± 1.2 μg/g, 1.6 ± 0.9 mg/g, 47.7 ± 22.5 mg/g, 4.6 ± 1.7 mg/g, and 7.3 ± 2.5 mg/g for uninvaded area, respectively (Mun and Lee *unpublished data*). Invasive plant species which grow faster than native species (Ehrenfeld 2003) and produce a large amount of aboveground biomass generate a large amount of litter and increase soil nutrient input through litter decomposition (Jo et al. 2017). Jo et al. (2017) found that monocultures of invasive plant species increase soil N availability through litter production. Additionally, basic cations act as essential resources for decomposers, as cations can alleviate litter acidity (Cornelissen and Thompson 1997; Swift et al. 1979). Moreover, some cations such as Ca^{2+} provide positive feedback on soil by changing soil acidity and fertility (Reich et al. 2005).

Conclusion

We assessed the contribution of *A. trifida* litter to the soil by measuring the decomposition rate. The study shows that *A. trifida* can significantly influence on the invaded soil environment with the fast decomposition and nutrient release. Nutrients release and decomposition of leaf litter were faster than those of stem litter aboveground. This shows that *A. trifida* leaf litter could act to supply resource to soil environments with high nitrogen content and low C/N ratio. Rapid nutrient release from decomposing litter before the active growth period may have a positive impact on the growth of the next generation of *A. trifida*, because its early germination allows it to utilize nutrient resources earlier than species that germinate later. Besides, nutrients released from decomposing litters and incorporated into the soil, could modify the chemical properties of soil where *A. trifida* is invaded. Invasive plants continuously modify environmental conditions, and such changes last for a long time even after the invasive plants have been removed. Disturbing the interaction between litter decomposition and plant growth can be an effective management practice (Corbin and D'Antonio 2012; Holdredge and Bertness 2011) because high soil nutrient content provides positive feedback to invasive plants (Meisner et al. 2012). Thus, knowledge of invasive plant-mediated changes is important because such changes can influence on management or restoration success (Hess et al. 2019; Keyport et al. 2019; Pickett et al. 2019). The results of this study are crucial for understanding the interactions between litter decomposition and soil nutrient cycling and can provide important information on invasive plant management. Further studies on the

Table 2 Summary of the amounts of organic matter and nutrients (N, P, K, Mg, and Ca) released into the soil during *Ambrosia trifida* litter decomposition after 22 months

	Organic matter	N	P	K	Mg	Ca
Initial amount (g/m^2)	9743	97.52	42.35	353.01	50.92	220.69
Remaining %	14.52	21.03	2.11	3.99	3.66	31.14
Released %	85.48	78.97	97.89	96.01	96.34	68.86
Released amount (g/m^2)	8328	76.49	40.25	349.02	47.25	189.55

organic chemical composition of litter types and the diversity and activities of soil microbes (e.g., bacteria and fungi) which involved in the decomposition process are needed to further understand the decomposition of *A. trifida*.

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