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Interactions between alien goldenrods (*Solidago* and *Euthamia* species) and comparison with native species in Central Europe

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ABSTRACT

Competitive interactions are among the crucial determinants of plant invasion. Most invasive species are more competitive than native species, with the strongest competition expected between species that share similar niches and/or those that are closely related. Because many habitats can be invaded by several non-native species, the competition between alien plants has an increasing importance. The American-origin goldenrods (*Solidago* and *Euthamia*) are exceptionally successful invaders in Europe. A replacement series experiment was performed, to identify the interactions between goldenrods in their invasive range. We determined what type of interferences dominated between the examined taxa by comparing the total yield of plants in mixtures and as a monoculture. Four alien goldenrods [*Solidago altissima* L., *Solidago canadensis* L., *Solidago gigantea* Aiton and *Euthamia graminifolia* (L.) Nutt] were studied and compared with native species (*Solidago virgaurea* L. and *Tanacetum vulgare* L.) that co-occur with them in natural conditions. The results show that the invasive *Solidago* species had similar competitive abilities. The invasive species that were examined, out-competed the native taxa. These results highlight the high competitiveness of *E. graminifolia*, which reduced the biomass of the other species. Such competitive abilities were related to underground competition. These results suggest the necessity to monitor this species as a potentially invasive taxon.

1. Introduction

Invasive plant species are major threats to biodiversity, because of their rapid rate of spread in plant communities and their ability to replace native vegetation. Invasions also alter landscape structure, ecosystem functions and services, as well as the local economy and human health and well-being (Pejchar and Mooney, 2009; Pyšek and Richardson, 2010). Therefore, biological invasions are pervasive global changes that challenge the conservation of biodiversity and natural resources (Simberloff et al., 2013). Many habitats are invaded by multiple species; thus, knowledge about the interactions between non-native species is important for nature conservation and management (Kuebbing et al., 2013; Kuebbing and Nuñez, 2015).

The invasive success of non-native plants depends on their biological traits, the environmental characteristics of the invaded areas and the biological interactions with native organisms (Catford et al., 2009; Ehrenfeld, 2010; Torres et al., 2013). Competition with resident vegetation is particularly essential for successful invasion (Gioria and Osborne, 2014; Kuebbing and Nuñez, 2015; Levine et al., 2003; Van Kleunen et al., 2010a; Vilà and Weiner, 2004). However, a superior competitive ability is not a prerequisite for successful invasion (Gioria and Osborne, 2014; McGlone at al., 2012), but non-native species that can dominate a vegetation often acquire available resources more efficiently and usually at the expense of native plants. The superior competitive ability of many invasive species for resources allows them to reduce plant species diversity and to form almost monospecific stands (Bottollier-Curtet et al., 2013; Čuda et al., 2015; Fenesi et al., 2015b; Gioria and Osborne, 2014; McGlone et al., 2012; Skálová et al., 2013). Therefore, the outcomes of species interactions between invasive and native species have been intensively studied, to increase the understanding of the mechanisms behind plant invasion (e.g., Bottollier-Curtet et al.,

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2013; Čuda et al., 2015; Novoa and González, 2014; Skálová et al., 2013) and to establish effective post-invasion restoration methods (e.g., Belgeri et al., 2014; Mangla et al., 2011; McGlone et al., 2012). The competitive strength is context-dependent, and can vary considerably across environmental gradients, life stages, disturbance regimes and plant species that are compared (Bottollier-Curtet et al., 2013; Čuda et al., 2015; Fenesi et al., 2015b; Leffler et al., 2014; Van Kleunen et al., 2010b). Nevertheless, many studies reveal the essential role of competitive interaction. It was shown that the invasive annual plant *Impatiens glandulifera* was more strongly competitive than the native *Impatiens noli-tangre*, whereas another invasive annual, *Impatiens parviflora*, was competitively the weakest. The competitive interactions were more important in terms of potential invasion success than changes in water and light availability and did not differ among the studied life stages (Čuda et al., 2015). Studies with the invasive herb *Solidago canadensis* and the native grasses *Elymus repens* and *Brachypodium pinatum* underline the competitive superiority of invasive plants, even in the presence of fire as a potentially altering factor (Fenesi et al., 2015b). The results of experiments in which native species that could dominate the vegetation were compared with invasive species, revealed the competitive superiority of invasive plants, at least in the early life stages (Bottollier-Curtet et al., 2013).

Typically, interspecific interaction between native and invasive taxa have been studied (Vilà and Weiner, 2004); nevertheless, interactions among non-native plant species are important, because it is becoming more common for many habitats to consist of numerous non-native species (Catford et al., 2012; Flory and Bauer, 2014; Kuebbing et al., 2013; Kuebbing and Nuñez, 2015). It has been assumed that the strength of competition between species depends on the degree of niche overlap (Hutchinson, 1957), and the strongest competition is expected among closely related species (Dayan and Simberloff, 2005; Violle et al., 2011). It can also be predicted that intraspecific competition is greater than interspecific competition, because individuals of the same species share similar resources. However, little empirical evidence is available regarding this issue (Mangla et al., 2011).

Goldenrod species from North America are among the exceptionally successful worldwide invaders (Pyšek, 1998; Semple and Cook, 2006; Weber and Jakobs, 2005). Invasions by goldenrod species into Europe have been observed for many years (Tokarska-Guzik, 2001), and goldenrod species occupy a vast area (Bartha et al., 2014; Fenesi et al., 2015a; Pyšek et al., 2002; Scharfy et al., 2009; Szymura and Szymura, 2013; Weber, 1998, 2001). Five representative goldenrod species (*Solidago* and *Euthamia*) inhabit central Europe; however, only one taxon, *Solidago virgaurea* L. agg., is native, and the other four taxa are of American origin: *Solidago gigantea* Aiton, *S. canadensis* L., *Solidago altissima* L. [=*S. canadensis* var. *scabra* (Muhl.) Torr. and Gray] and *Euthamia graminifolia* (L.) Nutt. Three introduced taxa (*S. gigantea*, *S. canadensis* and *S. altissima*) are widely distributed throughout Europe, whereas the range of *E. graminifolia* is small and is limited to a few locations (Dajdok and Nowak, 2006; Kompała-Bąba and Bąba, 2006; Weber, 2001). Because of their local high abundance and substantial environmental impact, the number and size of goldenrod populations should be controlled in Europe (Fenesi et al., 2015a; Sheppard et al., 2006; Skórka et al., 2010).

Despite the wealth of information about goldenrods and their environmental impact, knowledge about the interactions between these taxa in their new range, as well as their interactions with native species is relatively limited (Rebele, 2000; Tokarska-Guzik et al., 2014). Because alien goldenrod (*Solidago* and *Euthamia*) species were introduced from North America at approximately the same time in the eighteenth century, differences in colonization rates might reflect differences in their competitive ability (Weber, 1998, 2001; Weber and Schmid, 1998). Moreover, these species differ in biomass production and patterns of biomass allocation, as well as in phenology and growth dynamics (Szymura and Szymura, 2015), suggesting different competitive abilities (Park et al., 2003). Between these invasive taxa, strong competitive interactions should be observed, such as closely related species with overlapping niches. However *S . altissima*, *S . canadensis* and *S . gigantea*, which are the most widespread species, exist in multispecies field stands (Szymura and Szymura, 2013; Weber, 1998, 2000; Weber and Jakobs, 2005); thus, the nature of their interactions is unclear.

The aim of this study was to compare the interferences between non-native goldenrods introduced into Central Europe and those between alien taxa and two native species: *S. virgaurea* and *Tanacetum vulgare*, which often occur in a new range. Therefore, we performed a standard replacement series experiment (de Witt, 1960) and compared biomass production and allocation, as well as ramet height, number and flowering after 4 years of growth in a garden experiment. We answered the following questions: (i) how does the total biomass production differ between a monoculture and a mixture of species—does it increase, decrease or remain unchanged? (ii) how does interspecific competition alter biomass production and the allocation of particular species? and (iii) how does interspecific interference affect ramet height, number and flowering?

2. Materials and methods

2.1. The studied species

In the study, four alien goldenrod species were studied: *S. gigantea* Aiton, *S. canadensis* L., *S. altissima* L. and *E. graminifolia* (L.) Nutt. and two native species: *S. virgaurea* L. agg. and *Tanacetum vulgare* L. *E. graminifolia* is often referred to by its older, incorrect taxonomic name [*S. graminifolia* (L.) Elliot] in the European literature (Semple et al., 1981, 1984). Because of the morphological similarity between *S. canadensis* and *S. altissima* (Semple et al., 2015), these two species have been reported as a complex taxon *S. canadensis* s.l. (e.g., Abhilasha et al., 2008; Fenesi et al., 2015a; Sheppard et al., 2006). However, the rhizome systems of the taxa (Schmid et al., 1988), the morphological and micromorphological features of the leaf epidermis (Szymura and Wolski, 2011) and the details of the stems hairiness (Semple et al., 2015) differ.

The most widespread of the Europe goldenrods has a substantial environmental impact. The increase in alien *Solidago* species cover in vegetation patches is correlated with a decrease in the species richness of native plants (Fenesi et al., 2015a; Hejda et al., 2009; Szymura and Szymura, 2011), birds (Skórka et al., 2010) and ants (Lenda et al., 2013). The invasion of *Solidago* species also causes a decrease in the abundance, species richness and diversity of wild pollinators, including wild bees, hoverflies and butterflies (Moroń et al., 2009), and alters the mutual relationships between pollinators and the native flora (Fenesi et al., 2015a). The invasion of *Solidago* species also affects spontaneous succession in forests (Bornkamm, 2007) and abandoned fields (Bartha et al., 2014). Moreover, alien goldenrods alter the biogeochemical cycles and primary productivities of the invaded habitats (Chapuis-Lardy et al., 2006; Scharfy et al., 2010; Vanderhoeven et al., 2005, 2006).

All species examined were perennial herbs with rhizomes (or short stock) and belonged to the Asteraceae family. They contain single stems up to the inflorescence, and non-flowering leaf rosettes are often present. The inflorescences are fasciculate and thyrsoid (*S. altissima*, *S. canadensis*, *S. gigantea* and *S. virgaurea*), or form corymbose panicles (*E. graminifolia*, *T. vulgare*). The capit-