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Is spotted knapweed (*Centaurea stoebe* L.) patch size related to the effect on soil and vegetation properties?

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Abstract Spotted knapweed (*Centaurea stoebe* L. subsp. Micranthos (Gugler) Hayek) was first introduced in the 1890s from Europe into western North America, where it now occupies over three million hectares of rangeland and pasture in 14 states and two Canadian provinces, reducing forage production and causing economic damage. Despite many reported effects spotted knapweed can have on soils and native vegetation, it is not known whether patch size is correlated with these ecosystem-level effects. The objective of our study was to determine whether the effects of spotted knapweed on plant composition and soil properties was related to spotted knapweed patch size. We asked the following questions: (1) Are there differences in plant species richness and diversity between small and large knapweed patches? and (2) Do soil water and soil mineral nutrient properties change depending on knapweed patch size? Twenty-four knapweed patches, and paired natural grassland plots, were randomly selected within Lac du Bois Provincial Park, British Columbia, Canada. Knapweed patch size ranged from 6 to 366 m^2. Sampling and analysis revealed a significant effect of knapweed patch size on soil and vegetation properties. Soil P, soil temperature, and total dry plant biomass (g/0.25 m^2) increased, while soil N, soil C, and soil moisture decreased with patch size. Since our results show that spotted knapweed patch size is related to degree of soil alteration, it is important to consider size of patch when modeling the impact of spotted knapweed in North America. Since large patches of spotted knapweed seem to have a proportionately greater effect on soil chemistry properties, large patches may move the system further away from a point where it is possible to restore the site to pre-invasion conditions.

Keywords Grasslands · Rangelands · Invasive plant · Plant diversity · Plant litter · Soil nutrients

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Introduction

Many ecosystems in North America have been degraded by invasive plants. Invading species can replace existing vegetation and reduce native species, thus altering ecosystem diversity and function (Mack et al. 2000). In the most severe cases, non-native invasive species can alter the structure and dynamics of an ecosystem (Hobbs 1999; Ehrenfeld 2003). The mechanisms for this include increasing erosion (Lacey et al. 1989), altering nutrient cycling (Vitousek et al. 1987; Belnap and Phillips 2001; Duda et al. 2003; Rimer and Evans 2006), increasing incidence of plant diseases (Malmstrom et al. 2005), and potentially reducing or eliminating native populations (Huxel 1999; Mack et al. 2000; Masters and Sheley 2001). While it seems logical that the degree of invasion should be related to its effect on the ecosystem (Noss et al. 1995; Howard et al. 2004), there is little evidence to support such a claim. Invasive plants tend to grow in patches, with a non-uniform distribution across a landscape and variation in patch size. Should we expect larger ecosystem effects with larger patches?

The herbaceous spotted knapweed (*Centaurea stoebe* L. subsp. Micranthos [Gugler] Hayek [=*Centaurea maculosa* Lamarck (Ochsmann 2001)]) is a deeply taprooted perennial forb first introduced in the 1890s from Europe into western North America, where it now occupies over 3×10^6 ha of rangeland and pasture in 14 states and two Canadian provinces (LeJeune and Seastedt 2001; Story et al. 2006), reducing forage production (Harris and Cranston 1979) and causing economic damage (Hirsch and Leitch 1996). Disturbance aids in establishment of knapweed (Hobbs and Huenneke 1992). Once established, spotted knapweed is persistent and can tolerate low nutrient soils (Suding et al. 2004; LeJeune et al. 2006), drought (Berube and Myers 1982), and produce a seed bank with seeds viable for at least 8 years (Davis et al. 1993).

Spotted knapweed has been shown to alter soil ecosystem properties by elevating phosphorous within its rhizosphere (Zabinski et al. 2002; Thorpe et al. 2006), and increasing or decreasing (mostly reducing) soil C and N pools in native grasslands (Hook et al. 2004). In addition to altering soil properties, spotted knapweed can also reduce native plant species richness and diversity (Tyser and Key 1988; Ortega and Pearson 2005). Despite many accounts of the effect spotted knapweed can have on soils and native vegetation, it is not known whether scale, both spatial and temporal, is correlated with these ecosystem-level effects.

The objective of our study was to determine whether the effects of spotted knapweed on plant composition and soil properties was related to the size of spotted knapweed patches. Although spotted knapweed has been found to dominate large areas of land, it also has an inconsistent, patchy distribution. We asked the following questions: (1) Are there differences in plant species richness and diversity between small and large knapweed patches? and (2) Do soil water and soil mineral nutrient properties change along a gradient of knapweed patch size? We predicted a positive association between knapweed patch size and concentration of soil phosphorus, and a negative association between size of patch and concentration of soil nitrogen, soil carbon, and plant community richness and diversity. An understanding of how the size of a spotted knapweed patch affects plant and soil properties is an important consideration for grassland management, including eradication of knapweed and restoration to native plant communities. If larger knapweed patches have greater negative ecosystem effects it is critical that land managers focus their efforts on limiting patch size and eradicating or reducing large patches.

Methods

Site

The field site was in the high elevation (~900 m a.s.l.) grasslands of the Lac Du Bois (LDB) Grassland Provincial Park north of Kamloops, British Columbia, Canada. The park occupies approximately 15,000 ha and the site has been described by van Ryswyk et al. (1966). Annual precipitation is approximately 270 mm. The dominant grass species of the native grassland are *Festuca campestris* Rydb., *Achnatherum occidentale* (Thurb.) Barkworth ssp. *occidentale*, and *S. richardsonia* (Link) Barkworth with approximately 90% cover (van Ryswyk et al. 1966 and C. Carlyle, unpublished data). Livestock, including cattle, horses and sheep, have grazed LDB for over a century. Approximately 50 years ago, range management shifted to spring/fall rotational cattle grazing at approximately one cow per hectare, with a 1-year rest period between grazing. Spotted knapweed first established in LDB approximately 40 years ago and has a patchy distribution.

Experimental design

Twenty-four patches of spotted knapweed were randomly selected within a 3,000 ha area in LDB. A knapweed patch was identified as a group of at least 10 stems, with stems no further than 1 m from its neighbor. Patches were separated by at least 20 m. Patch size was estimated by measuring the length of the longest straight line through the patch, then measuring the length of the longest second line through the patch perpendicular to the first line, and calculating the product. Paired 0.25 m^2 plots were created, with one plot located at random exactly 5 m inside a knapweed patch, and the other located 5 m due North from the edge of the patch. If the patch size was smaller than 100 m^2, the plot was placed in the approximate centre of the spotted knapweed patch.

Sampling

Soil measurements were taken on August 19, 2005. Soil moisture was measured using a TDR soil moisture meter fitted with the 20 cm soil rod (Spectrum Technologies, Inc.). Soil temperature was taken at a depth of 10 cm using a digital temperature probe. At each corner of the plot, the top 10 cm^3 of soil was collected and the four samples combined. The soil was air dried, stones were removed by hand, and the soil was passed through a 2 mm sieve. Soil carbon (%) and nitrogen (%) was analyzed with the CE-440 Rapid Analysis Elemental Analyzer, Exeter Analytical, Inc. Soil phosphate (mg l^{-1}) and potassium (mg l^{-1}) were measured using Palintest© test kits. The mineral concentration of mg l^{-1} is equivalent to mg kg^{-1}.

Above ground live plant biomass and litter were harvested on August 23–26, 2005. The collected biomass was sorted to species, oven dried at 80°C for at least 48 h, and weighed. Litter was also similarly oven dried and weighed.

Statistical analysis

Paired *t* tests were used to compare soil and plant parameters taken inside knapweed patches and in native grassland. A Bonferroni pairwise procedure was done to correct for multiple sampling. To determine the effect of knapweed patch size, we first calculated the difference in soil and plant parameters between the 24 samples inside knapweed patches to their neighboring grassland plots. This was done in order to reduce the potential for underlying site effects. We calculated linear regressions of the effect of knapweed area on the calculated difference of soil (moisture, temperature, C, N, P, K) and vegetation (live plus litter biomass, live biomass, litter biomass, knapweed biomass, total species richness, total Shannon diversity) parameters of paired plots. In addition, we calculated linear regressions of the effect of knapweed area on the same parameters as listed above with knapweed biomass (g/0.25 m^2) as a covariate. All statistical analyses were done using Systat 8 (Systat 1998).

Results

Litter, total species richness and total diversity were higher in the native grassland compared to the

Table 1 Mean soil and vegetation parameters measured within the 24 knapweed community and 24 native grassland community plots with standard error in parentheses

	Knapweed community	Grassland community	*P* value
Soil variables			
Volumetric water content (%)	**6.40 (0.54)**	**9.32 (0.73)**	**0.046**
Temperature (°C)	**29.29 (0.33)**	**27.41 (0.37)**	**0.002**
Total carbon (%)	**5.05 (0.31)**	**7.13 (0.23)**	**<0.001**
Total nitrogen (%)	**0.25 (0.02)**	**0.41 (0.03)**	**<0.001**
Total phosphate (mg l^{-1})	**12.64 (1.13)**	**5.20 (0.32)**	**<0.001**
Total potassium (mg l^{-1})	**535.80 (29.74)**	**385.60 (25.85)**	**0.006**
Vegetation variables			
Live plus litter biomass (g)	83.18 (5.23)	96.87 (8.12)	1.000
Live biomass (g)	71.59 (4.82)	64.50 (6.14)	1.000
Litter biomass (g)	**12.88 (1.93)**	**33.71 (3.68)**	**<0.001**
Total species richness	**4.08 (0.28)**	**5.56 (0.42)**	**0.035**
Total Shannon's diversity (H′)	**0.36 (0.06)**	**0.69 (0.09)**	**0.011**

Values in bold represent significant differences between the two communities ($P < 0.05$). *P* values were adjusted based on the Bonferonni test knapweed community (Table 1). There was no difference in total live plus litter biomass and live biomass between knapweed and grassland communities. All measured soil variables were found to be significantly different between the knapweed and native grassland communities; volumetric water content (VWC), carbon, and nitrogen had lower values in the knapweed community, while temperature, phosphate, and potassium had higher values (Table 1).

Total live plus litter biomass (Fig. 1a), live biomass (Fig. 1b), and knapweed biomass (Fig. 1d) were all positively related to knapweed patch size ($P \leq 0.05$). The other vegetation variables were not affected by area (Fig. 1).

Knapweed patch size seemed to affect all measured soil variables except for potassium (Fig. 2). Soil volumetric water content (VWC) (Fig. 2a), soil carbon (Fig. 2c) and soil nitrogen (Fig. 2d) were negatively associated with patch size, but only soil C had a $P < 0.05$. Soil N and VWC had P values less than 0.10, which suggests a trend in the data. Soil temperature (Fig. 2b) and soil phosphate (Fig. 2e) were positively associated with knapweed patch size.

Linear regressions of the effect of patch size with knapweed abundance (biomass) as a covariate showed that total live plus litter biomass and live biomass were positively affected by knapweed biomass and the interaction between patch size and knapweed biomass, but not by patch size alone (Table 2). Soil carbon was negatively affected by knapweed patch size and soil total phosphate was positively affected by patch size, but soil carbon and phosphate were not affected by knapweed biomass or the interaction between patch size and biomass (Table 2). The regression model for soil temperature

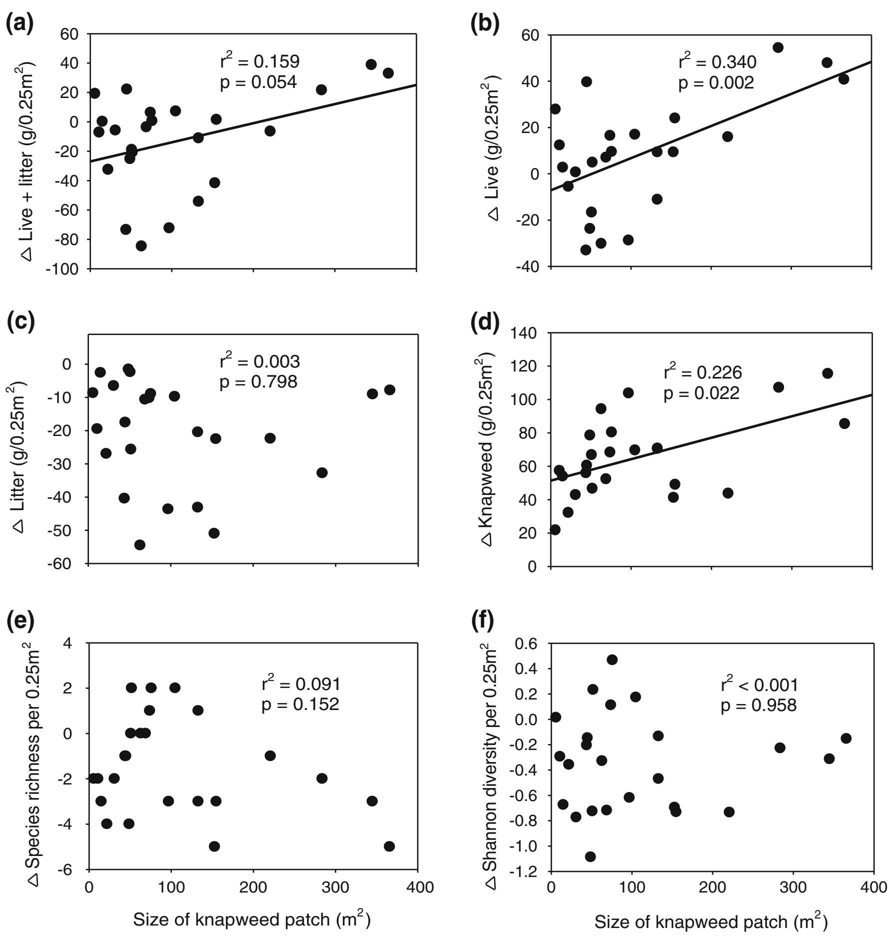

Fig. 1 Size of spotted knapweed patch as it affects the difference between measured vegetation variables inside the knapweed patch and the paired grassland community plot: **a** Total dry aboveground live biomass plus litter; **b** Dry aboveground live biomass; **c** Dry litter; **d** Dry knapweed; **e** Species richness; and **f** Shannon diversity index

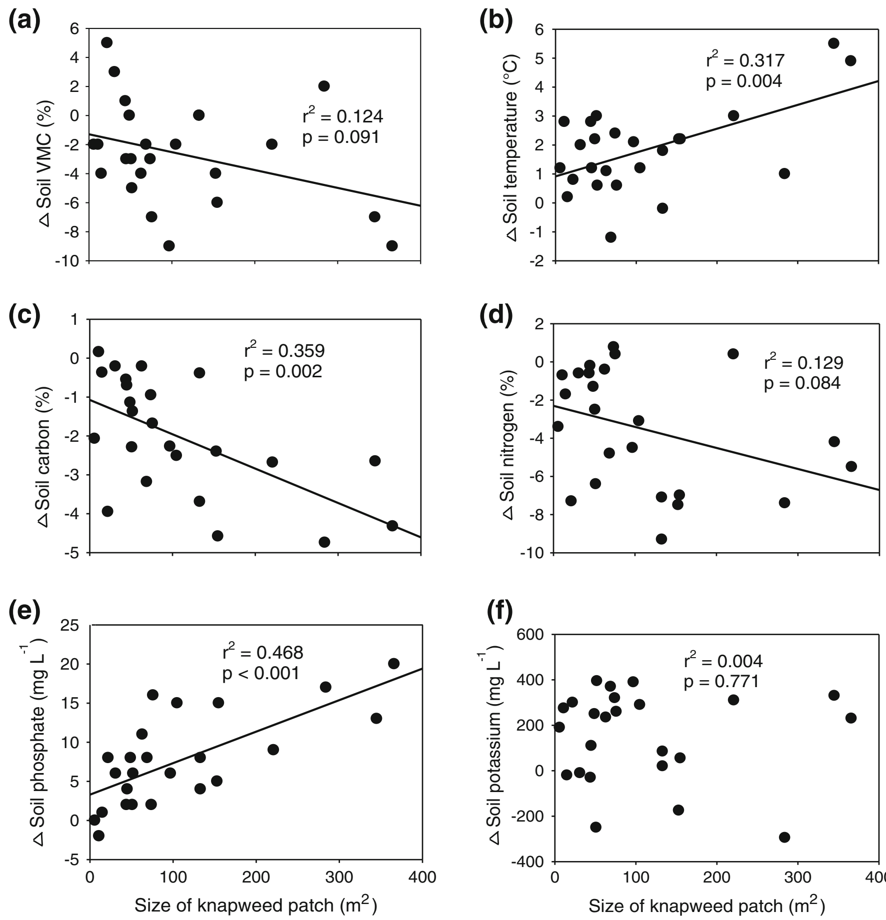

Fig. 2 Size of spotted knapweed patch as it affects the difference between measured soil variables inside the knapweed patch and the paired grassland community plot: **a** Soil volumetric water content (VWC); **b** Soil temperature; **c** Soil carbon; **d** Soil nitrogen; **e** Soil phosphate; and **f** Soil potassium

was significant but neither patch size nor biomass alone was significant.

Discussion

For the first time, we provide evidence that the size of an invasive plant patch is related to vegetative and soil properties. Not surprisingly, our results show that soil chemistry and vegetation properties differ between spotted knapweed patches and native grassland communities in Lac du Bois Provincial Park, British Columbia, Canada. Past research has also shown that spotted knapweed can alter soils (Zabinski et al. 2002; Hook et al. 2004; Thorpe et al. 2006) and vegetation (Tyser and Key 1988; Ridenour and Callaway 2001; Ortega and Pearson 2005). Our research extends our understanding of spotted knapweed by demonstrating that knapweed patch size is related to changes in soil P and soil C, even when knapweed abundance (biomass) is included as a covariate. Because this was a correlative study we cannot say with certainty that the environmental conditions inside the knapweed patches we sampled were caused by knapweed. However, by linking to previous research, especially relating to soil chemistry, we can strengthen the conclusions of our study.

In answer to our first question, there were no differences in plant species richness and diversity based on spotted knapweed patch size. The effect of knapweed on richness and diversity is independent of patch size. Tyser and Key (1988) found that spotted knapweed can reduce species richness by approximately two species per 0.1 m^2 in fescue grasslands in Glacier National Park, USA. We also found a reduction in native species richness, from about 5.6 in grassland to 3.1 (4.1–1 [not including spotted knapweed] in Table 1) in knapweed patches per

Table 2 Linear regression models of the effect of knapweed patch size on change in vegetation and soil variables inside and outside 24 knapweed patches in a native grassland, with knapweed biomass as a covariate

Dependent variable	Effect	*P*(2 Tail)	Model
Live plus litter biomass	Patch size	0.212	$\mathbf{F = 4.355; P = 0.016}$
	Knapweed biomass	**0.014**	
	Size × Biomass	**0.026**	
Live biomass	Patch size	0.445	$\mathbf{F = 8.097; P = 0.001}$
	Knapweed biomass	**0.007**	
	Size × Biomass	**0.024**	
Litter biomass	Patch size	0.187	$F = 0.837; P = 0.490$
	Knapweed biomass	0.185	
	Size × Biomass	0.154	
Total species richness	Patch size	0.904	$F = 1.294; P = 0.304$
	Knapweed biomass	0.208	
	Size × Biomass	0.426	
Total Shannon's diversity	Patch size	0.334	$F = 0.392; P = 0.760$
	Knapweed biomass	0.742	
	Size × Biomass	0.338	
Soil volumetric water content	Patch size	0.204	$F = 1.931; P = 0.157$
	Knapweed biomass	0.123	
	Size × Biomass	0.292	
Soil temperature	Patch size	0.094	$\mathbf{F = 3.236; P = 0.044}$
	Knapweed biomass	0.763	
	Size × Biomass	0.100	
Soil carbon	Patch size	**0.048**	$\mathbf{F = 4.927; P = 0.010}$
	Knapweed biomass	0.241	
	Size × Biomass	0.872	
Soil total nitrogen	Patch size	0.819	$F = 1.561; P = 0.230$
	Knapweed biomass	0.256	
	Size × Biomass	0.591	
Soil total phosphate	Patch size	**0.041**	$\mathbf{F = 7.164; P = 0.002}$
	Knapweed biomass	0.263	
	Size × Biomass	0.441	
Soil total potassium	Patch size	0.927	$F = 0.081; P = 0.970$
	Knapweed biomass	0.737	
	Size × Biomass	0.942	

$P < 0.05$ are in bold

0.25 m^2 plots. In addition, species diversity in a knapweed patch was about half that of the natural grassland, which reflects the dominance of knapweed in terms of its relative biomass. The fact that knapweed patch size does not seem to affect species diversity and richness indicates that knapweed plants are competitively dominant and have negative neighbor effects even at small spatial scales.

Studies suggest that invasive plants often increase biomass and net primary productivity, alter nutrient availability, and produce litter with higher decomposition rates than co-occurring native species (Ehrenfeld 2003). We found no difference in dry live aboveground biomass between knapweed and grassland communities. However, there was almost a three-fold reduction in litter within the knapweed patch. Such differences in litter mass are often accompanied by changes in soil organic matter, and soil carbon was higher in the grasslands. We suspect that decomposition rate of knapweed leaves is greater than the native grasses (see Cornelissen and Thompson 1997). Abiotic conditions can also influence the decomposition rate of litter (Davidson and Janssens 2006; Austin and Vivanco 2006). For example, Austin and Vivanco

(2006) found that a reduction in intercepted solar radiation on litter caused lower decomposition of organic matter. In other words, the rate of decomposition was highest under full sunlight. We found higher soil temperature and lower soil volumetric water content within knapweed patches, and these differences increased with size of patch, suggesting a mechanism (greater incident solar radiation) for increasing decomposition rate in larger patches.

We found conclusive evidence for our second question, does soil water and soil mineral nutrient properties change depending on the size of knapweed patch? All measured soil properties differed by knapweed patch size except for potassium. The mineral nutrient with the greatest response was soil phosphate. Soil phosphate was greater in patches of spotted knapweed, which has also been shown by Zabinski et al. (2002) and Thorpe et al. (2006). Thorpe et al. (2006) suggested that catechin may increase P in the rhizosphere through chelation of Ca. Catechin is a polyphenol found in spotted knapweed that can be important in the complexation of Fe, Al, and Ca, including the precipitation of Ca–P compounds (Stevenson and Cole 1999). Suding et al. (2004) showed that reduction of soil P weakened the ability of *Centaurea diffusa* (diffuse knapweed, another invasive knapweed) to tolerate neighbor competition in grazed grassland. If low concentration of soil P similarly affects the growth and competitive ability of spotted knapweed, the increase in soil phosphate we found in knapweed patches might favor knapweed growth and competitive ability. Since spotted knapweed seems to enhance soil P, and our results show that this effect is magnified with patch size, knapweed invasion may facilitate further invasion and a concomitant increase in patch size.

Previous studies have shown that plant invasions do not always result in consistent changes in soil properties. For example, Hook et al. (2004) found that spotted knapweed might increase or decrease soil C and N in native grasslands in Montana, U.S.A. Our study finds that soil C and N were lower in knapweed patches than native grassland, and negatively associated with size of patch. Soil C responded similarly to knapweed patch size even when considering knapweed biomass as a covariate. This result is perhaps conservative considering that cattle grazed the native grassland but likely did not graze the knapweed. Even though litter was higher in the native grassland compared to knapweed patches, if the native grassland was not grazed the grassland soils might have had even higher amounts of litter and soil N (Derner et al. 1997). The decreases in knapweed soil N and C may be associated with high uptake rates of these elements, which might be driven by a large biomass and high tissue nutrient concentration of spotted knapweed. Tilman (1988) suggests that a plant species is competitively dominant when it reduces an essential resource below the minimum level a neighboring species can grow. Therefore, if low soil N in knapweed patches is caused by knapweed growth, the competitive dominance of knapweed may be due to its ability to reduce soil N which not only reduces species diversity but might prevent restoration to the native grassland community.

Potassium is usually the most abundant of the major nutrient elements in soil (Blake et al. 1999). Size of knapweed patch did not affect soil K at our experimental site, but knapweed patches had higher levels of soil K than native grassland. Bezemer et al. (2006) found that grasses depleted soil K to a greater extent than forbs, and our results support this finding.

We show that scale is an important consideration in understanding the effect of an invasive, in this case spotted knapweed, on soil properties, but timing since arrival could be an indirect factor to consider. Altered soils may be the driving mechanism that provides a suitable environment to facilitate future invasions and decrease native biodiversity (Wolfe and Klironomos 2005; MacDougall and Turkington 2005). The presence of spotted knapweed, and in some cases knapweed patch size, was correlated with different soil properties. It is not clear whether knapweed patch size and abundance were related to time of arrival. Once an alien plant arrives at a new site, community invasion is regulated by characteristics of the invading plant and the existing community (Lawton 1986). It is still unclear what scale, spatial or temporal, is most relevant when addressing the effects of exotic plants on soil communities. Bezemer et al. (2006) experimentally tested the effects on soil properties of different grassland grass and forb species grown in monoculture in 3 m^2 plots in the Netherlands and the United Kingdom. They found significant effects in soil mineral nutrients between plant species after only 2 years. What we do not know is whether the magnitude of the effect continues to increase over time.

Time since arrival is an important consideration in the science of species invasion but has not been adequately addressed (see Pyšek and Jarošík 2005; Herben 2009). The increased soil changes we found in large knapweed patches could be due to patch size, but it might be due to longer site occupancy of the invader. We suggest that size of spotted knapweed patches in British Columbia might be related to timing of arrival; the larger the patch, the longer the invasive has been established on site. However, the fact that patch size is related to an increase in soil P and a decrease in soil C is relevant regardless of whether time since arrival is correlated.

Our results show that size of spotted knapweed patch in Lac du Bois Provincial Park, B.C., Canada is related to degree of soil alteration. It is important to consider size of patch when modeling the impact of spotted knapweed in North America. Large patches of spotted knapweed seem to have a proportionately greater effect on important soil chemistry properties, in particular soil P and soil C. The size of spotted knapweed patches may facilitate increases in soil P through knapweed's interaction with catechin. Larger patches may also magnify a reduction in soil C by increasing photodegradation of litter. Large patches may move the system further away from a point where it is possible to restore the site to pre-invasion conditions. Thus, patch size is an important consideration in the management of invasive species.

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