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Structural equation modeling reveals complex relationships in mixed forage swards

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A B S T R A C T

Relationships among vegetation components in perennial pastures are complex, particularly those including grasses, weeds, legumes, and other forbs. Where herbicides are used for broadleaf weed control, a trade-off may exist between the benefits of weed removal and legume loss. Few studies have separated the contribution of different vegetation components to total forage yield, either prior to or after spraying. Herein we use Structural Equation Modelling (SEM) to quantify relationships among grasses, legumes (*Medicago sativa* L. or *Trifolium* spp.), a common noxious weed (*Cirsium arvense* (L.) Scop), and other forbs, at two locations within the Parkland region of central Alberta, Canada. After removal of broadleaf vegetation with herbicide, we quantified changes in forage relative yield ratio (RYR) for two years. The SEM approach revealed marked differences in the relationships among sward components between sites. At the more mesic site, abundant thistle biomass had little influence on other sward components and no benefit was observed post-spraying from weed removal. In contrast, even low levels of thistle biomass suppressed grass and legume biomass at the more xeric location, and post-spraying responses revealed benefits from weed removal. Unexpectedly, legumes were found to suppress grass biomass at both sites, suggesting strong interspecific competition between forage types. Subsequent removal of legumes appeared to release grass biomass from competition within sprayed plots, as exemplified by increased forage yields two years after spraying. These results highlight the complexity within temperate perennial pastures, and add clarification to the potential short-term impacts of weeds and legumes to overall sward dynamics and forage production.

1. Introduction

Pastures are dynamic in composition and prone to invasion by noxious weeds such as Canada thistle (*Cirsium arvense* L.). This particular weed is found worldwide, including temperate regions of Canada and the northern United States (Holm et al., 1997; Wilson and Kachman, 1999). Presence of Canada thistle is known to decrease productivity in annual crops (O'Sullivan et al., 1982; O'Sullivan et al., 1985), as well as the yield of forage in pasture (Grekul and Bork, 2004).

In addition to the competitive nature of Canada thistle, justification for the control of this weed is reinforced through regulations mandating its control (e.g. Province of Alberta (2008)). Options available for controlling this species include mowing (Beck and Sebastian, 2000; Schreiber, 1967), tillage (Lukashyk et al., 2008), burning (Tranicek et al., 2005), biological techniques such as forced ungulate grazing (De Bruijn and Bork, 2006), as well as herbicides (Enloe et al., 2007; Grekul and Bork, 2007). Although the most effective suppression of pasture weeds often requires an integrated approach (Masters and Sheley, 2001), broadleaf herbicides remain a popular and effective method for weed control (DiTomaso, 2000).

Invasion of noxious weeds into pastures results in complex sward dynamics (Tracy and Sanderson, 2004; Sanderson et al., 2007; Bork et al., 2007) and includes negative impacts on

Abbreviations: CT, Canada thistle; LI, Lake Isle; N, nitrogen; PCF, parkland conservation farm; RYR, relative yield ratio; SEM, structural equation modeling.

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neighboring forage plants. Canada thistle is an effective competitor for available resources and space (Donald, 1990) and reduces forage growth (Reece and Wilson, 1983; Grekul and Bork, 2004), accessibility to livestock (Haggar et al., 1986) as well as species diversity (Stachlon and Zimdahl, 1980). However, the full agronomic, ecologic and economic impacts of noxious weeds within pastures generally remain poorly understood (Lym and Duncan, 2005).

Many studies have examined the production benefits of grass-legume mixtures (Sleugh et al., 2000; Frame and Harkess, 1987; Holt and Jefferson, 1999). Legumes are valued for the ability to directly increase forage yields (Malhi et al., 2002; Popp et al., 2000), but can also lead to facilitation (i.e. improved growth) of neighboring plants (Nyfeler et al., 2009). Presence of legumes within mixed swards can increase the availability of soil nitrogen (N) for neighboring grasses through N fixation in association with *Rhizobium* bacteria (Walley et al., 1996). However, facilitation of growth in pastures may be beneficial to both neighboring grasses and weeds. Previous studies on Canada thistle have demonstrated that this species responds positively to fertilization in the absence of weed control (Grekul and Bork, 2007). In mixed swards that include perennial grasses, weeds and legumes, simultaneous competition for resources and facilitation from enhanced nutrient availability will determine net forage productivity. Outcomes will therefore vary depending on species proximity, competitiveness and abundance.

Weed control with broadleaf herbicides in mixed pastures is likely to lead to a trade-off between the desirable control of competitive weeds and the undesirable loss of beneficial legumes. Although generally assumed that legume removal will reduce net forage yields within mixed pasture swards, this remains untested. As legumes can provide competition against grasses for resources (Hill, 1990), the removal of legumes may allow grasses to increase in growth and this could partly or fully offset the opportunity cost of legume removal, a response that may be further augmented by weed removal. In annual crop rotations legume removal has led to increased grain yield and protein concentration (Cutworth et al., 2010; Jefferson et al., 2013). Thus, testing the ability of grasses to compensate for the removal of legumes, including under variable weed presence, is important for pasture management.

Plant community dynamics are difficult to quantify using conventional yield loss methodology, in part due to the spatial heterogeneity present in pastures, which likely accounts for the variable forage losses found between environments (Grekul and Bork, 2004). However, contemporary methods to evaluate empirical relationships among environmental phenomenon have greatly improved, and now include techniques such as Structural Equation Modeling (SEM). Essentially, SEM aims to generate strong and distinct links between theoretical and experimental ideas (Grace et al., 2010). The ability to disentangle causal relationships and test competing models and theory (as opposed to null hypotheses) are key strengths of SEM methods. Thus, SEM provides a framework to decipher complex networks involving numerous response and predictor variables (Grace et al., 2010). Because of its statistical strength and applicability, SEM approaches have been employed in a wide range of environmental and ecological studies (e.g., Shipley, 2000; Grace, 2006; Jonsson and Wardle, 2010; Lamb et al., 2011a, 2011b; Stewart et al., 2011). To our knowledge SEM methods have not been applied to study weed impacts in pasture.

The goal of this investigation was to quantify relationships among grass, legume and weed (i.e. Canada thistle) abundance in two contrasting perennial pastures, prior to spraying and after spraying with non-selective broadleaf herbicide. Specific objectives were to 1) quantify the competitive or facilitative relationships between grasses, legumes, Canada thistle (CT), and other forbs prior to spraying, and 2) evaluate the net effects of varying levels of CT removal and legume loss following herbicide application on total forage production in mixed pasture swards.

2. Materials and methods

2.1. Study sites

Two established pastures were selected for this investigation from 2005 to 2007 inclusive, both situated in the Aspen Parkland natural sub-region of central Alberta, Canada. Sites were internally uniform (i.e. slope, aspect, drainage, etc.), and contained a minimum of 30% legume cover, with Canada thistle densities averaging 18.0 and 23.5 stems m^{-2} among plots at the PCF and LI sites, respectively, during the first year. Typical of pastures in the region, legume and thistle populations were not uniformly distributed across each site and this heterogeneity was used to facilitate the assessment of inter-specific relationships among vegetation components.

Lake Isle (LI) is located approximately 70 km NW of Edmonton, Alberta (53° 39′ N; 114° 43′W) on an imperfectly drained riparian floodplain with a Gleyed Black Chernozemic soil. The LI site was an old growth pasture (age >20 years) with a diverse plant community dominated by timothy (*Phleum pratense* L.), smooth brome (*Bromus inermis* Leyss), and substantial amounts of clover (primarily *Trifolium repens* L.). The Parkland Conservation Farm (PCF) site was located near Mundare, Alberta (53° 39′ N; 112° 20′ W), approximately 90 km east of Edmonton, on a well-drained upland with an Orthic Black Chernozemic soil. This sward had been seeded in 1999, six years prior to the initiation of the study, and was dominated by meadow brome (*Bromus riparius* Rehm.), smooth brome, and alfalfa (*Medicago sativa* L.).

Average annual precipitation from the Environment Canada weather stations nearest the LI and PCF sites, was 530 and 403 mm, respectively. While precipitation levels in 2005 were near average, rainfall in 2006 and 2007 at both sites was generally below norms from June through August (Fig. 1). The average annual temperature for the region is 4.3 °C, with a typical frost free period of about 110 days.

2.2. Study design and sampling

Our study design included two complementary components. First, an *in-situ* empirical examination of pasture composition was done prior to spraying in 2005 at each site. This was followed up with the examination of sward responses post-spraying in 2006 and 2007 to assess net forage responses to broadleaf removal with herbicide application in 2005. At each site, 100 permanent 1 m^2 plots were established along a series of linear transects with a minimum 1 m buffer from other plots. Plots were permanently marked to facilitate relocation for repeated measurement. Each plot included a centrally located 0.25 m^2 (i.e. 50 × 50 cm) quadrat within which all biomass measurements were taken.

Biomass was harvested annually from each of the 0.25 m^2 permanent quadrats at peak growth (mid-July to early August) and sorted to perennial grasses, legumes, CT, and other broadleaf forbs. Prior to harvest, the density of CT stems was quantified within each quadrat. Biomass was oven-dried at 60 °C to constant mass and weighed. Both study sites were fenced to prevent grazing prior to sampling in mid-summer. Moderate grazing with cattle occurred on both sites each fall after the first killing frost, which helped prevent excess litter accumulation and allowed sites to remain consistent with typical land use practices in the region.

In the fall of 2005, 80 of the 100 plots at each site were randomly selected and sprayed with the residual broadleaf herbicides aminopyralid (120 g ae ha^{-1}) and 2,4-D (1440 g ai ha^{-1}) using an all-