NASA/NPS/UAF Final Report

INVASIVE PLANT SPREAD IN BURNED LANDS OF INTERIOR ALASKA

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Cover Photo: *Melilotus officinalis* invades a burn site in the Nenana Burn along the Parks Highway north of Denali National Park and Preserve. Photo by Katie Villano.

Abstract

The increasing area affected by wildfire in interior Alaska offers invasive plants an avenue for spread into intact boreal ecosystems. To identify areas that are most susceptible to invasive plant colonization and spread, we conducted intensive invasive plant surveys within burn perimeters along the Dalton, Steese and Parks Highways. Invasive plants were both most abundant along roadsides and most frequently found moving into burned habitat in the Nenana Burn on the Parks Highway, and the two southernmost burn complexes on the Dalton Highway. Climatic factors such as altitude and latitude influence the distribution of invasive plants across the landscape. On a smaller scale, larger numbers of successful invasive plant colonization events occur in moderately sloped sites with high levels of propagule pressure from roadside populations. Invasive plant spread and population growth in burned sites is influenced by species-specific responses to different burn severity levels. Land managers can use remotely sensed burn severity maps in conjunction with roadside invasive plant distribution maps to effectively manage the spread of invasive plants in burned areas of Alaska. Susceptible burn areas to target management efforts for *Crepis tectorum* are moderately or lightly burned sites with the invasive present within 400 m on the roadside. Target areas for managing the spread of *Melilotus officinalis* in burns should include high severity burn sites with dense populations of the species on the directly adjacent roadside.

Acknowledgements

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Introduction

Non-native plant invasions have seriously altered community structure and ecosystem functioning in habitats around the globe (Levine et al. 2003; Vitousek et al. 1997). Invasive species are among the top causes of losses in native biodiversity worldwide (Sala et al. 2000), and play a role in the imperilment of nearly half the extinct and endangered species in the U.S. (Wilcove et al. 1998). Non-native plant invasions can also change ecosystem properties such as nutrient cycling, hydrology, and fire regimes (Busch and Smith 1995; D'Antonio and Vitousek 1992; Vitousek and Walker 1989).

Due to the undeveloped nature of large areas of the state, Alaska has remained less affected by invasive species than the rest of the United States. Alaska's non-native plants have largely been restricted to human population centers and roadsides. In the past, cold climate and limited human population were thought to restrict the movement of non-native plants into northern ecosystems (Carlson and Shepherd 2007). As the climate warms and the levels of both anthropogenic and natural disturbance grow, boreal habitats are becoming increasingly susceptible to non-native plant invasions. Several species have recently spread into vulnerable natural disturbance areas adjacent to roads such as wildfire scars and glacial river floodplains (Conn et al. 2008; Villano 2008; Cortés-Burns et al. 2007; Wurtz et al. 2006).

Warmer summer temperatures and decreased precipitation in Alaska have dramatically increased wildfire disturbances in the past few decades (Bachelet et al. 2005; Stocks et al. 2000; Overpeck et al. 1997), and their frequency, severity, and extent are predicted to continue to increase in the future (Flannigan et al. 2001). In the record breaking fire years of 2004 and 2005, 11.2 million acres of land burned in Alaska (Fitzgerald 2006; Fig. 1). In boreal Alaska, as in other types of ecosystems, areas affected by fire tend to be more vulnerable to invading non-native plant species than undisturbed areas (Villano 2008; Floyd et al. 2006; Dimitrakopoulos et al. 2005; D'Antonio 2000; Vitousek 1986). The increasing area of land burned by wildfire could facilitate the spread of invasive plants into Alaska's wilderness areas.

Figure 1. Record wildfire seasons in 2004 and 2005 created millions of acres of burned habitat in interior Alaska. Vast areas of burned land, as on the Dalton Highway (above left), could create vulnerable avenues for the spread of invasive plants such as *Crepis tectorum* (above right) throughout Alaska in areas away from the human disturbance footprint.

Researchers have only just begun investigating the relationship between wildfire and invasive plant species in Alaska. In black spruce forests of Alaska, wildfire increases the vulnerability of an area to colonization by invasive plant species (Villano 2008). However, the specific factors that determine site invasibility remain unclear. Recent studies have suggested that burn areas adjacent to areas of high human activity are the most vulnerable to invasive plant colonization (Cortés-Burns et al. 2007; Cortés-Burns and Carlson 2006), and that the amount of invasive plant propagule pressure from the roadsides likely determines the locations where invasives are able to spread into burns (Villano 2008; Cortés-Burns et al. 2007). This observation, however, has never been directly tested in Alaska. Evidence from a greenhouse study, which held propagule pressure constant, showed that invasive plants germinate and grow better in soils from fire scars that burned at low severity (Villano 2008). These low severity burn soils offered invasive plants a less competitive environment than high severity sites where native herbs and bryophytes had rapidly colonized (Villano 2008).

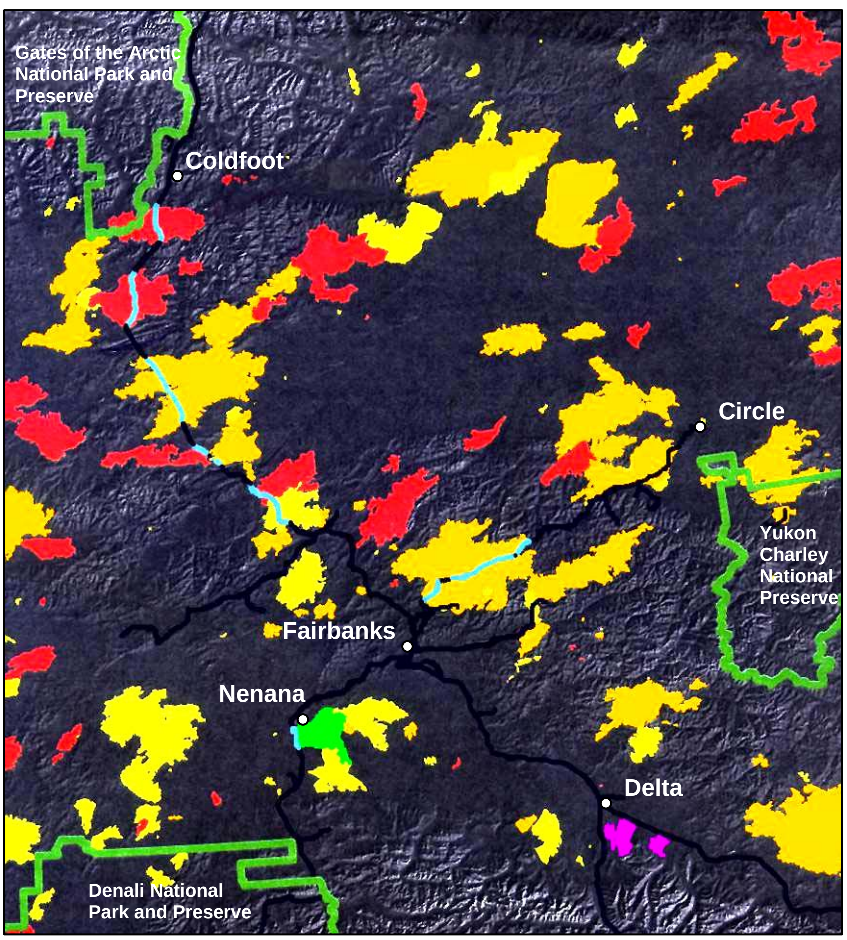
To date, field surveys of invasive plants in burned areas of Alaska have been too coarse to detect biotic or abiotic factors that may facilitate the spread of invasive plants into the vast backcountry. The objectives of this study seek to fill in these vital information gaps so that land managers might effectively protect Alaskan lands from the adverse impacts of invasive plant species. We conducted an intensive field study along the Dalton, Steese, and Parks Highways in Interior Alaska to investigate the following questions:

1. Where do invasive plants currently occur within burn perimeters?
2. What determines how invasive plants are distributed across the landscape?
3. Can levels of invasive plant infestation in burned areas be explained by propagule pressure from adjacent roadside invasive plant populations?
4. Do environmental variables explain levels of invasive plant infestation in burned areas?
5. Does pre-fire vegetation type explain levels of invasive plant infestation in burned areas?
6. Does post-fire vegetation type explain levels of invasive plant infestation in burned areas?
7. Does burn severity explain levels of invasive plant infestation in burned areas?

Methods

To address our research questions, we surveyed burned areas adjacent to major roadways throughout Interior Alaska (Figure 2). We surveyed a total of 200 miles along the Dalton, Steese, and Parks Highways in July 2007. The burns surveyed on the Dalton Highway were bounded to the south by Erickson Creek, and to the north by Coldfoot. Listed from south to north, the burns surveyed on the Dalton included the Erickson Creek Burn (2003) and unnamed burns (2000-2005), Fort Hamlin Hills Burn (2004), Ray River Burn (2005), Dall City Burn (2004), North Bonanza Burn (2005), and Chapman Creek Burn (2005). On the Steese Highway, we surveyed within the Boundary Burn (2004) perimeters, and on the Parks Highway, we surveyed the Nenana Burn (2006).

The survey focused on three invasive plant species, *Crepis tectorum* L. (narrowleaf hawksbeard), *Melilotus officinalis* Lam. [formerly *Melilotus alba* Medikus] (white sweetclover), and *Vicia cracca* L. (bird vetch). All three species are relatively widespread non-native plants in interior Alaska (Lapina et al. 2007). *C. tectorum* and *M. officinalis* have been documented spreading from the roadside into burned areas along the Dalton, Parks, and Alaska Highways (Villano 2008; Cortés-Burns et al. 2007; R. Gronquist, pers. comm.; J. Heys, pers. comm.). *V. cracca* was observed moving into unburned patches within burn perimeters on the Dalton Highway (R. Gronquist, pers. comm.; S. Seefeldt, pers. comm.). In addition, these species were selected for the invasiveness traits they possess that present significant threat to Alaska’s wild lands. *M.*



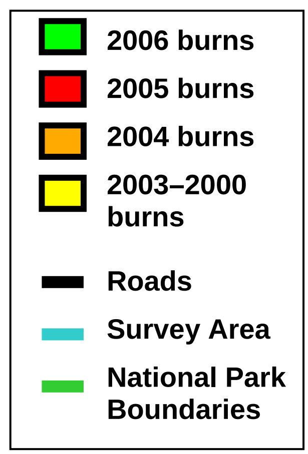


Figure 2. Map of study area in interior Alaska.

officinalis and *V. cracca* can alter ecosystem processes by fixing nitrogen in the typically nutrient poor soils or interior Alaska (AKEPIC 2005). *C. tectorum* has potential to spread great distances into burned areas through its wind-dispersed seeds (Royer and Dickinson 2004).

Along roadsides we surveyed for presence and population sizes of our three focal invasive species. To identify factors that might influence burn site invasibility, we surveyed belt transects within burned areas, beyond the road shoulder and evidence of human disturbance, for movement of invasive plants into the burn. We collected data in each transect on the burn severity, native vegetation characteristics, and environmental variables.

On the Dalton and the Parks Highways, we sampled every quarter mile within burn perimeters of all target burns. Highway mile posts served as sampling points, and then sampling points alternated sides of the road every quarter mile. Due to minimal invasive plant presence on roadsides within the Boundary Fire on the Steese Highway, we sampled every half mile on the south side of the road. At every sampling point, we took a GPS reading and surveyed the roadside for our focal invasive plants species 20 m to each side of the GPS point (40 m total) (Figure 3). To quantify infestation levels along the roadside, we recorded whether our focal species was scattered (1-25 individuals widely spaced), in patches (26-500 individuals in clusters), or continuous (>500 individuals evenly dispersed throughout the transect). Infestation levels along the roadsides between sampling points were also recorded.

If the area adjacent to the sampling point was burned within 50 m of the road, we surveyed a 50 m x 10 m belt transect running into the burn perpendicular to the road (figure 3). We collected GPS points at both the beginning and end of the transect, and recorded the transect azimuth and elevation so that transects could be relocated for future study. To understand environmental variables that might influence invasive plant establishment in burned areas, we recorded slope and aspect at the midpoint of the transect. If the area adjacent to the sampling point was unburned, we conducted a roadside survey only.

To understand the changes in native plant community structure following movement away from the road, and the dispersal distances of our focal invasives, we divided the belt transect into five 10 m x 10 m quadrats (Figure 3). Within quadrats 1, 3, and 5, we collected intensive vegetation and burn severity data. Variables collected in these quadrats included: native vegetation cover and composition, burn severity class of the substrate and vegetation (5= unburned, 4= scorched, 3= lightly burned, 2= moderately burned, 1= highly burned; as in AIFETG 2007), burn microvariablity within quadrats (% unburned, % vegetated charred organics, % unvegetated charred organics, and % mineral soil), and pre-fire vegetation class (Viereck 1992). We also took photos of each quadrat.

When our focal invasives were present within or near the burn transect, we recorded the species identity, distance into burn, number of clusters in the infestation, population size class (1-5, 6-25, 26-50, 51-150, 151-500, >500), and phenology. At each invasive plant cluster in the burn, we measured the depth of organic soil that remained after the fire, the spot burn severity class, and the soil surface type (live moss or lichen, dead moss, upper duff (fibric layer), lower duff (sapric layer), or mineral soil). Photos of each infestation were also taken.

All statistical analyses were performed using SAS v.9.1 (SAS Institute, Cary, North Carolina), with the exception of the ordinations (PC-ORD v. 4, McCune and Mefford, 1999). To test if geographic location influenced the levels of invasive plant infestation along roadsides and in burns, we used G-tests for independence, logistic regression, and linear regression. To test if invasives were evenly distributed along the roadside within burn perimeters, we used a test of spatial aggregation. To determine if the level of infestation in burn areas could be explained by levels of roadside infestation, or propagule pressure, we used analysis of variance (ANOVA). After determining that levels of roadside infestation significantly influenced the levels of infestation within burn transects, we used this variable as a covariate in ANOVAs aimed at determining if pre-fire vegetation class or burn severity class influenced invasive population size or number of invasive clusters within burns. We also tested if the probability of invasive plant presence in burn transects was independent of burn severity or pre-fire vegetation using G-tests for independence. We used an ordination approach to determine if post-fire vegetation composition influenced invasive plant infestation levels in burned areas. Finally, to determine the geographic, environmental, pre-fire vegetation, post-fire vegetation, burn micro-variation, and burn severity variables that best explained the variation in invasive plant population size and number of invasive clusters in burned areas, we used Akaike's information criterion (AIC) model selection and stepwise linear regression.

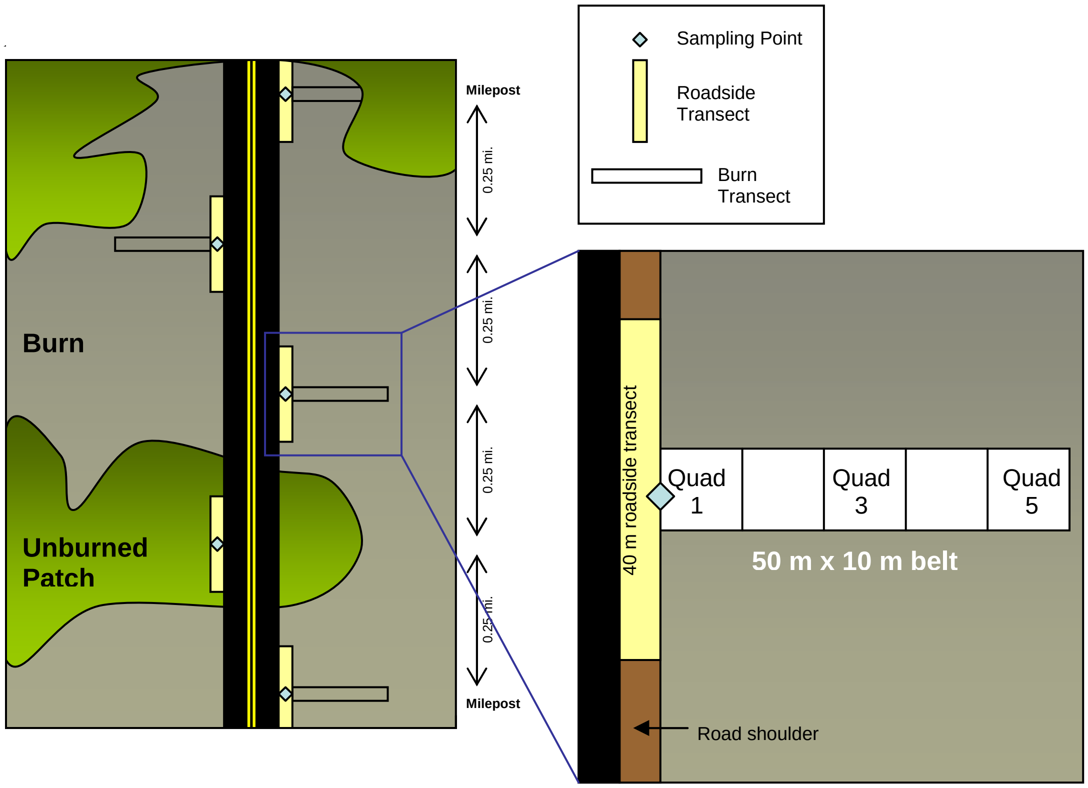


Figure 3. Survey and sampling design. Sampling points were staggered on both sides of the road every 0.25 miles within burn perimeters. Roadside invasive plant surveys were conducted in a 40 m transect centered on each sampling point. Where adjacent land was burned within 50 m of the road shoulder, a 50 m x 10 m belt transect was surveyed for native vegetation, burn severity, environmental variables, and invasive plant presence.

Results

Geographic Distribution

On Roadsides within Burn Perimeters

Melilotus officinalis had the broadest distribution along roadsides in our survey area of all our focal invasive species, occurring in 48% of the 508 roadside transects we conducted, despite the fact that *M. officinalis* did not occur in our transects on the Steese Highway (Table 1). Continuous *M. officinalis* infestations dominated 10.5% of roadside transects on the Dalton Highway and 20.8% of roadside transects on the Parks Highway (Table 1), indicating high levels of propagule pressure in these regions. *Crepis tectorum* was present in 18.9% of roadside transects, and occurred along all three highways (Table 1). The Dalton Highway had higher levels of *C. tectorum* infestation along the roadside than did the Parks or Steese Highways (Table 1). *Vicia cracca* occurred in 2.1% of roadside transects along the Dalton Highway (Table 1). While *V. cracca* did not show up in any transects on the Steese or Parks Highways, it did occur in a few patches between transects on these highways.

Using tests of spatial aggregation, we found that the focal invasive plants were evenly distributed along the Parks Highway in the Nenana Burn ($X^2_{(47)}$ = 2032.4, P = <0.001), and on the Dalton Highway in the burn complex between the Eliot Highway Junction and the Yukon River ($X^2_{(62)}$ = 87.7, P = 0.01), in the Ray River-Fort Hamlin Hills burn complex ($X^2_{(39)}$ =434.3, P =<0.001), and in the Dall City Burn ($X^2_{(70)}$ = 104.7, P = 0.005). This result reflects the fact that one of our three focal species was present in nearly every roadside transect we surveyed in these burn perimeters.

The distribution of our focal invasives along the Dalton Highway within the North Bonanza and Chapman Creek burn perimeters was sporadic and clumped. Likewise, invasives were sporadically distributed along the Steese Highway within the Boundary Burn. Of the 79 roadside transects we surveyed in the Boundary Burn, only four had any of our focal species present.

Table 1. Proportion of sampling points with no (N), scattered (S), patchy (P), or continuous (C) invasive plant infestations on the roadside within recent burn perimeters. Data on this table represent roadside transect data taken at all burned and unburned sampling points within burn perimeters (every quarter mile on Dalton and Parks; every half mile on Steese).

Highway	**# transects**	***Crepis tectorum***				***Melilotus officinalis***				***Vicia cracca***			
		N	S	P	C	N	S	P	C	N	S	P	C
Dalton	381	76.6	14.4	7.1	1.8	54.3	18.1	17.1	10.5	97.9	0.8	1.0	0.3
Parks	48	93.8	6.3	0.0	0.0	2.1	12.5	64.6	20.8	100.0	0.0	0.0	0.0
Steese	79	94.9	3.8	1.3	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Total for all regions	508	81.1	12.0	5.5	1.4	56.5	14.8	18.9	9.8	98.4	0.6	0.8	0.2

Within Burned Habitat

Within the burn perimeters of our target burns 50.8% of the sampling points were actually burned, reflecting the patchy nature in which these fires burned the landscape. Of those burned sampling points, 12.5% had infestations of one of our focal species present within the burned habitat (Table 2). *Crepis tectorum* occurred in 6.9% of burned sites, and *Melilotus officinalis* was present in 5.6% of the burned sites (Table 2). We did not find *Vicia cracca* moving into burned areas at any of our sampling points.

Highest levels of infestation within burned habitat occurred in the Ray River-Fort Hamlin Hills burn complex on the Dalton Highway (50% of burn transects were infested with *C. tectorum* or *M. officinalis*; Table 3). The Nenana Burn on the Parks Highway showed the second highest level of infestation, with 36.4% of burn sites being colonized (Table 2). The majority of Nenana Burn sites were infested with *M. officinalis* (Table 2). Following the Nenana Burn, the burn complex between the Eliot Highway Junction and the Yukon River showed the third highest level of infestation, with 27.8% of burn sites being colonized by *C. tectorum* (Table 3).

Infestations in burned sites within the Dall City and North Bonanza burn perimeters along the Dalton Highway were few and isolated (Table 3). The Dall City burn had a single prominent infestation of *M. officinalis* near No Name Creek. The invasive had spread both north and south of the creek on the west side of the road, with over 100 individuals penetrating up to 30 m into the burned habitat. Within the North

Bonanza Burn, we found two burned sites with *M. officinalis* (both with 6-25 individuals penetrating less than 1 m into the burn) and one site with C. *tectorum* (with 1-5 individuals penetrating 23.5 m into the burn) occurring near Alaska Pipeline Pump Station No. 5.

None of our focal species occurred in burned sites within the Boundary Burn perimeters on the Steese Highway (Table 2). Similarly, we found none of our focal species in burned habitat in the Chapman Creek Burn, the northern most burn we sampled on the Dalton Highway (Table 3).

When our focal invasive species occurred in burn areas, they penetrated an average distance of 13 (± 2.7) m away from the road shoulder into burned habitat (Table 4). Of the three focal species, *C. tectorum* tended to spread the greatest distances into burned habitat, averaging 18.2 m into burned sites where it was found (Table 4). The maximum distance we found *C. tectorum* penetrating into burned areas was 50.5 m. Population sizes of our focal species averaged 29 (± 8) individuals when they occurred in burned areas, with larger populations of both *C. tectorum* and *M. officinalis* tending to occur in burns on the Dalton Highway, than in burns on the Parks Highway (Table 5).

Table 2. Percent burned transects with focal invasive plants present within burned habitat along the Dalton, Parks and Steese Highways in Interior Alaska. Significant differences (P<0.05) between highways for each invasive species are indicated by different letters (in columns).

Highway	**# transects**	***Crepis tectorum***	***Melilotus officinalis***	***Vicia cracca***	**All species**
Dalton	171	8.2 a	2.9 a	0.0 a	11.1 a
Parks	22	4.5 ab	31.8 b	0.0 a	36.4 b
Steese	28	0.0 b	0.0 a	0.0 a	0.0 c
All Regions	221	6.9	5.6	0.0	12.5

Table 3. Percent burned transects with invasive plants present within burned habitat by fire complex on the Dalton Highway. Fire complexes are listed from south to north. Significant differences (P<0.05) between highways for each invasive species are indicated by different letters (in columns).

Fire Complex	***Crepis tectorum***	***Melilotus officinalis***	***Vicia cracca***	**All species**
Eliot Hwy Junction to Yukon River Burns (2000-2005)	25.0 a	0.0 a	0.0 a	25.0 a
Ray River (2005)-Fort Hamlin Hills (2004) Burns	30.0 a	20.0 b	0.0 a	50.0 a
Dall City Burn (2004)	0.0 b	1.9 a	0.0 a	1.9 b
North Bonanza Burn (2005)	1.7 b	3.3 ab	0.0 a	5.0 b
Chapman Creek Burn (2005)	0.0 b	0.0 a	0.0 a	0.0 b

Table 4. Mean maximum distance (m) from roadsides that invasive plants were found in infested burn transects. Values are means (+ 1 se). Significant differences (P<0.05) between highways for each invasive species are indicated by different letters (in columns).

Highway	***Crepis tectorum***	***Melilotus officinalis***	***Vicia cracca***	**All species**
Dalton	18.9 (4.5) a	3.0 (1.8) ab	0.0 (0.0) a	14.7 (3.7) a
Parks	8.0 (0.0) ab	8.9 (2.6) b	0.0 (0.0) a	8.8 (2.3) a
Steese	0.0 (0.0) b	0.0 (0.0) a	0.0 (0.0) a	0.0 (0.0) a
All Regions	18.2 (4.2)	6.4 (1.9)	0.0 (0.0)	13.0 (2.7)

Table 5. Mean invasive plant population size in infested burn transects. Numbers here are the means (+ 1 se) of the median # stems for the population size class present in the transect. Significant differences (P<0.05) between highways for each invasive species are indicated by different letters (in columns).

Highway	***Crepis tectorum***	***Melilotus officinalis***	***Vicia cracca***	**All species**
Dalton	35.3 (15.1) a	32.3 (12.4) a	0.0 (0.0) a	34.6 (11.7) a
Parks	3.0 (0.0) a	16.3 (7.9) a	0.0 (0.0) a	15.3 (7.3) a
Steese	0.0 (0.0) a	0.0 (0.0) a	0.0 (0.0) a	0.0 (0.0) a
All Regions	33.9 (14.5)	22.2 (6.8)	0.0 (0.0)	28.6 (8.5)

Landscape-Level Factors that Influence Invasive Plant Infestation in Burned Areas

Highway

The likelihood of one of our focal species occurring on the roadside within a burn perimeter was influenced by the highway the burn was located on ($G_{(2)}$ = 139.2, P = <0.0001). Similarly, the identity of the highway that ran through the burn also influenced the likelihood of a burn being invaded ($G_{(2)}$ = 15.94, P = 0.0003). Highest proportion of burn sites with invasive plants present both on roadsides and in burns occurred on the Parks Highway, followed by the Dalton Highway (Tables 1 and 2). The highway on which the burn was located did not, however, significantly influence the distance invasives were able to travel into the burn, nor the invasive plant population size within the burned habitat (Tables 4 and 5).

Latitude

The proportion of transects infested with the focal species decreased as latitude increased ($F_{(1)}$ = 4.28, P = 0.05; Figure 4A). Latitude was able to explain 18.4% of the variation in where invasives occurred along the roadside. Likewise, the proportion of burn sites with invasives spreading into them from the road decreased the more northerly the sites were located ($F_{(1)}$ = 4.51, P = 0.05, R^2 = 0.192; Figure 4B).

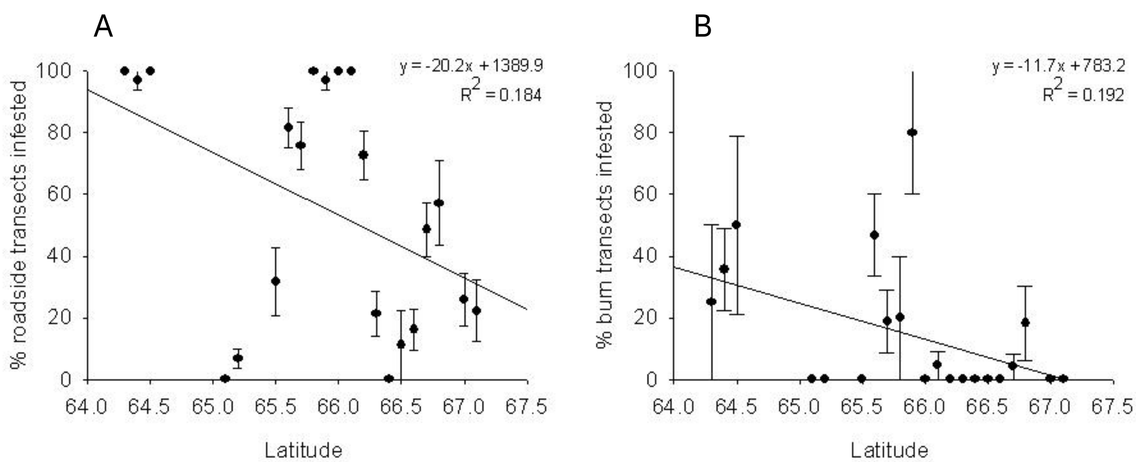


Figure 4. Latitude and the proportion of roadside (A) and burn (B) transects infested by focal invasive plant species. Filled circles represent mean (± 1 se) invasive plant presence in 0.1 degree latitude increments.

Altitude

Altitude explained a startling amount of variation (76.3%) in the distribution of the three invasive plant species along roadsides in our sample area. Likely reflecting both temperature and moisture constraints at higher elevations, the occurrence of invasives along the roadside decreased as elevation increased ($F_{(1)}$ = 67.53, P = <0.0001; Figure 5A). The proportion of burn sites with invasive plants colonizing burned habitat also decreased as altitude increased ($F_{(1)}$ = 21.7, P = 0.0002, R^2 = 0.533; Figure 5B).

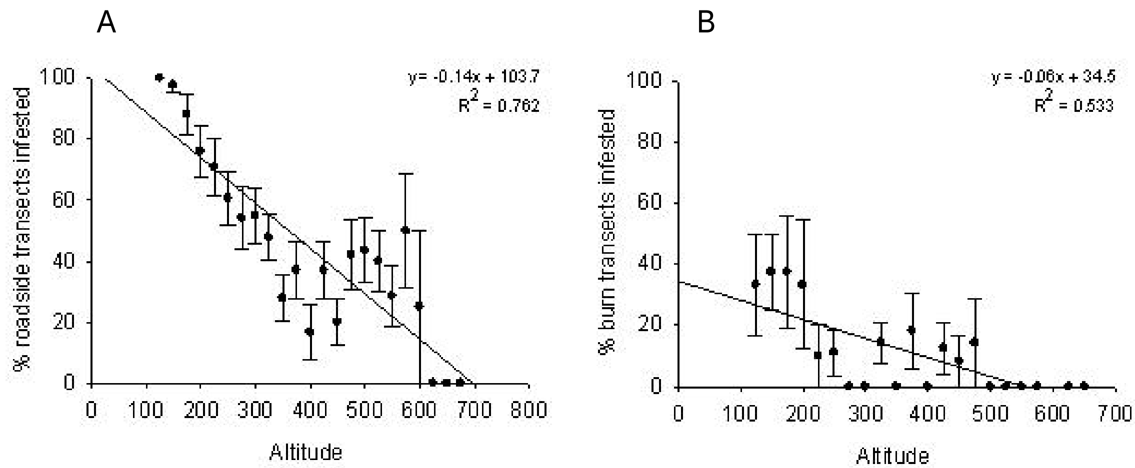


Figure 5. Altitude and the proportion of roadside (A) and burn (B) transects infested by focal invasive plant species. Filled circles represent mean (± 1 se) invasive plant presence in 25 m altitude increments.

Site-Level Factors that Influence Invasive Plant Infestation in Burned Areas

Propagule Pressure from Roadsides

To assess the influence of propagule pressure on invasive plant colonization in burned areas we used two response variables: the number of invasive plant clusters occurring in the burn transect, and the mean population size of the clusters. To determine if the different levels of propagule pressure could better explain these response variables than invasive plant presence on the roadside alone, we used an additive ANOVA approach.

Invasive presence on the roadside increased the number of focal invasive plant clusters and the average invasive plant population size that occurred within burned sites (number of clusters— $F_{(1)} = 17.94$, $P = <0.0001$; population size—$F_{(1)} = 3.62$, $P = 0.05$). When added to the model, the level of roadside infestation was better able to explain variation in the number of invasive clusters in a burn site than did roadside presence alone, doubling the model R^2 value. Burn transects with patches or continuous levels of roadside infestation had 87% and 89%, respectively, greater number of invasive clusters than did burn transects with scattered invasives on the roadside. For average invasive population size in burned sites, however, the addition of roadside infestation level to the model did not increase the model performance. These data suggest that the number of invasive clusters (or number of successful colonization events) is directly related to the level of propagule pressure from the roadside invasive populations, while the population sizes of within those clusters is likely more directly reflects the time elapsed since the initial colonization event and the habitat suitability.

Melilotus officinalis only colonized burn sites if there was a seed source present on the adjacent roadside, and both the number of invasive clusters and population size were influenced by roadside presence (number of clusters: $F_{(1)} = 12.28$, $P = 0.0006$; population size: $F_{(1)} = 6.85$, $P = 0.009$). The level of roadside infestation helped explain variation in number of invasive clusters and in invasive population size in burn sites better than did roadside presence alone, doubling the R^2 value of both models. Burn transects with continuous *M. officinalis* on the roadside had three times greater average population sizes than did burn transects with patches on the roadside.

Unlike *M. officinalis, C. tectorum* was documented in four burn transects without occurring in the adjacent roadside transect. The closest seed source for these sites was 200 – 400 m away, suggesting that this species is capable of colonizing burned areas large distances away from the seed source. Despite this capacity for long-distance dispersal, the number of *C. tectorum* clusters and the mean population size were larger when it was present on the roadside (number of clusters: $F_{(1)} = 27.25$, $P = <0.0001$; population size: $F_{(1)} = 8.48$, $P = 0.004$). The addition of roadside infestation level into the model only marginally increased the model performance for both response variables (only 1% more variation was explained in both models). This suggests that only low levels of propagule pressure are needed for *C. tectorum* to colonize and spread in a burned area.

Because *Vicia cracca* did not occur in any of our burned transects, it will not be discussed further in the results.

Our data showed that propagule pressure was an important factor determining the distribution of our focal invasive plants in burned areas. As a result, we included the level of roadside infestation as a covariate in all further ANOVA models, or limited the data set to only sites with propagule pressure on the roadside in tests of independence.

Environmental Variables

Within burn transects that had invasive propagule pressure from the road, the slope of the burn site influenced the likelihood of focal invasive plants occurring in a burn transect ($G_{(3)} = 8.96$, $P = 0.03$). The greatest percentage of burns infested were sites with moderate slopes of 6 to 10 degrees (Figure 6A). Invasive plants never occurred in burn sites with a slope greater than 10 degrees. Aspect did not significantly influence the likelihood of a transect being infested, however, flat sites and north-facing sites tended to be less frequently invaded than sites facing other directions (Figure 6B).

Using both AIC model selection, the environmental variables that best explained the number of invasive plant clusters in a burn transect and the population sizes of those invasive plant clusters were identified. When selecting from all geographic, environmental, pre-fire vegetation, post-fire vegetation, burn micro-variation, and burn severity variables, the model best explaining the number of invasive plant clusters in a burn transect included latitude, slope, and the level of propagule pressure from the roadside (regression model: # of invasive plant clusters = 9.47 – 0.15 latitude + 0.04 slope + 0.22 propagule pressure, $F_{(3)}= 4.61$, $P= 0.004$). The model best explaining invasive plant population sizes of clusters in a burn transect included slope, and burn severity of the vegetation (regression model: invasive plant population size = 21.9 + 1.09 slope – 5.13 vegetation severity, $F_{(3)}= 4.61$, $P= 0.004$).

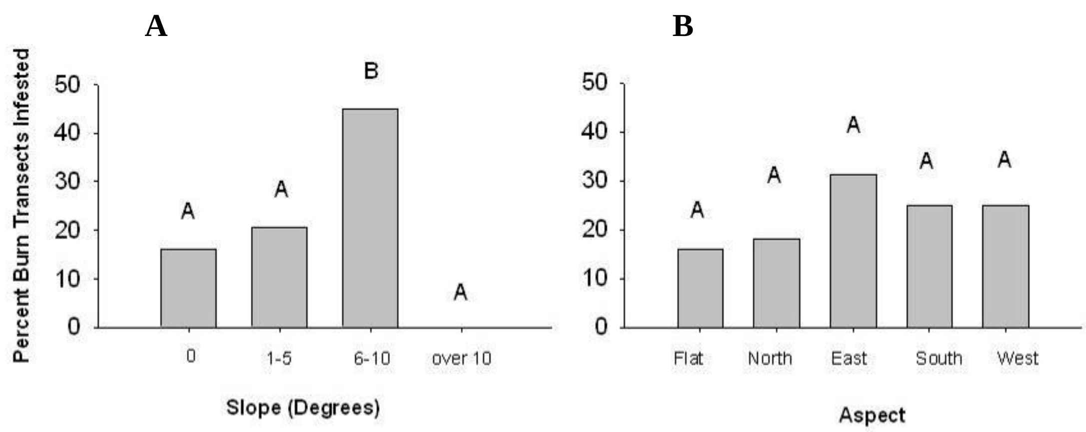


Figure 6. Percent burn transects infested by focal invasive plants in sites with different slopes (A) and aspects (B). Data here represent only sites where invasive plants were present on the roadside. Significant differences between slopes or aspects are indicated with different letters and were determined using G-tests of independence.

Pre-fire Vegetation

Overall, a greater percentage of sites that were open forest or woodland before the fire were infested by one of our focal species than in sites that were other stand types (Figure 8A). No focal invasive plants occurred in sites that were dominated by shrubs prior to fire (Figure 8B), or in sites that were scrub or herbaceous vegetation types (Figure 8A). *C. tectorum* occurred in a greater percentage of sites that were open canopy forest prior to burning than in other forest types, while *M. officinalis* occurred in a greater percentage of woodland sites (Figure 8A). The number of invasive plant clusters and the population size of clusters within burned transects were not influenced by pre-fire vegetation type for any species.

Post-fire Vegetation

Using ordination (non-metric multi-dimensional scaling, the Bray-Curtis distance measure), we found a weak relationship between post-fire vegetation composition and invasive plant establishment (Figure 9). Burn transects that were infested with our focal invasive species tended to score lower on axis 1 than sites not infested (Figure 9). This axis was negatively correlated with substrate burn severity score (Pearson's r=-0.268) and vegetation burn severity score (r=-0.262), suggesting that those factors may influence both vegetation composition and likelihood of invasion.

Figure 7. *Crepis tectorum* grows in a transect at mile 299.5 of the Parks Highway. The invasive plant was found within 10 meters of the road shoulder in a lightly burned area. Photo by Katie Villano.

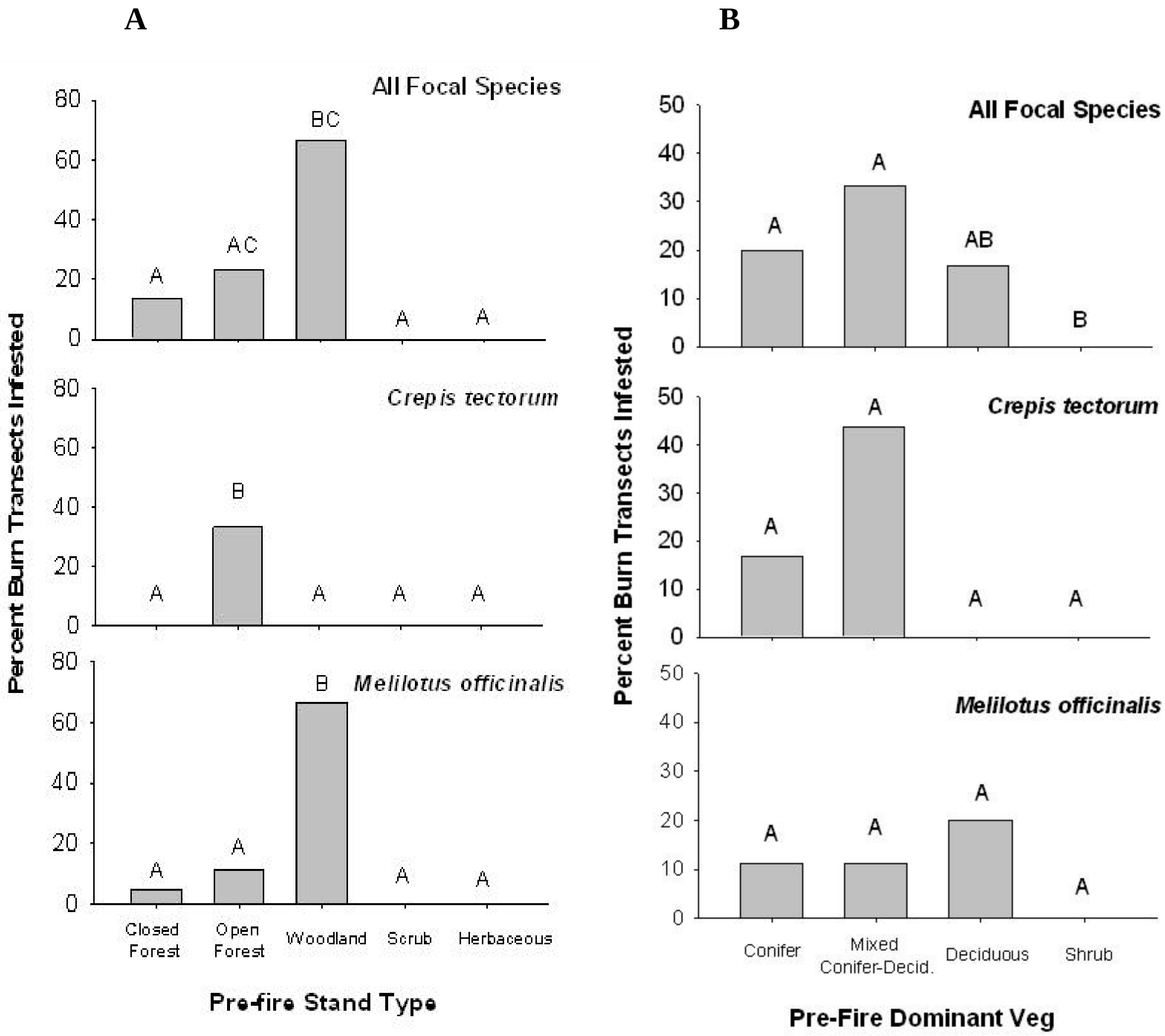


Figure 8. Percent burn transects infested by focal invasive plants in sites with different pre-fire stand type (A) and pre-fire dominant vegetation (B). Data here represent only sites where invasive plants were present on the roadside. Significant differences between pre-fire vegetation types are indicated with different letters and were determined using G-tests of independence.

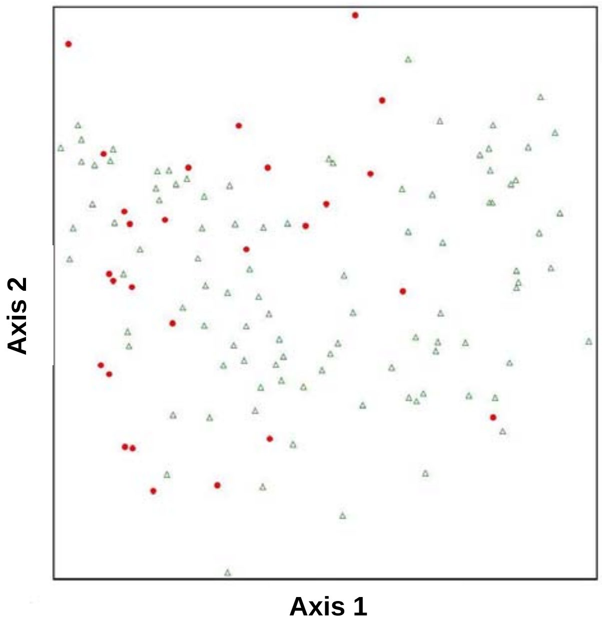


Figure 9. NMS ordination of sites by invasion status. Sites with at least one invasive species present in the transect are indicated by red dots; uninvaded sites are represented by green triangles. Axis 1 is negatively correlated with burn severity sore, indicating sights with a severity score of 5 (unburned) were rarely invaded.

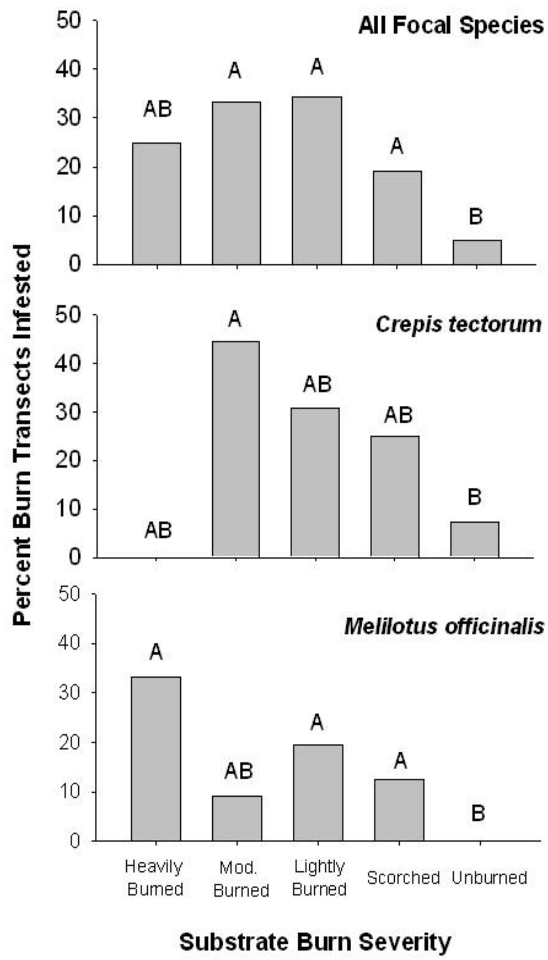


Figure 10. Percent burn transects infested by focal invasive plants in sites of different burn severities. Data here represent only sites where invasive plants were present on the roadside. Significant differences between burn severity levels are indicated with different letters and were determined using G-tests of independence.

Burn Severity

Of a burn transects with invasive plants present along the adjacent roadside, burn severity influenced the likelihood of one of our focal species occurring within the burned habitat (Substrate severity- $G_{(4)} = 13.87$, $P = 0.008$; Vegetation severity- $G_{(4)} = 11.71$, $P = 0.02$). Because substrate severity and vegetation severity were tightly correlated (Pearson's $R = 0.78$, $P = <0.0001$), we will discuss only the influence of substrate severity on invasive plant colonization in burned areas.

Transects that were unburned within the first ten meters from the road shoulder were rarely infested with our focal species (Figure 10). Across species, moderately or lightly burned transects were more likely to have invasive plant present within burned habitat than other burn severities (Figure 10). A greater number of invasive plant clusters tended to occur in lightly burned sites than in sites of other burn severities, while greater invasive plant population sizes within these clusters tended to occur in areas that were moderately burned (Table 6).

This pattern, however, differed between our focal species. Moderately burned transects were more frequently invaded by *C. tectorum* (Figure 10) and had greater population sizes than transects that were other burn severity levels (Table 6), but the greatest number of *C. tectorum* clusters occurred in transects that were lightly burned (Table 6). While *C. tectorum* was never found in areas that were heavily burned (Figure 10), *M. officinalis* occurred in high severity burn transects more frequently than it did in less severely burned transects (Figure 10). A greater number of *M. officinalis* clusters and greater population sizes also tended to occur in high severity burn transects than in transects of other burn severities (Table 6).

Table 6. Mean number of invasive plant clusters and mean population size of clusters within burn transects of different substrate burn severity levels. Values are means (+ 1 se). Significant differences (P<0.05) between burn severity levels for each invasive species are indicated by different letters (in columns).

Substrate Burn Severity	***Crepis tectorum***		***Melilotus officinalis***		**All focal spp.**	
	# of clusters	population size	# of clusters	population size	# of clusters	population size
Heavily Burned	0.0 (0.0)a	0.0 (0.0)b	0.3 (0.3)a	12.7 (12.7)a	0.3 (0.3)ab	9.5 (9.5)ab
Moderately Burned	0.4 (0.2)a	38.5 (35.9)a	0.2 (0.2)a	0.8 (0.8)b	0.4 (0.2)ab	23.8 (21.6)a
Lightly Burned	0.8 (0.4)a	4.9 (3.7)ab	0.3 (0.1)a	1.4 (0.6)b	0.6 (0.2)a	3.4 (1.4)ab
Scorched	0.4 (0.3)a	8.4 (6.5)ab	0.3 (0.2)a	2.9 (1.8)ab	0.3 (0.2)ab	5.3 (2.6)ab
Unburned	0.1 (0.1)a	1.9 (1.9)b	0.0 (0.0)a	0.0 (0.0)b	0.1 (0.1)b	0.7 (0.6)b

Table 7. ANOVA F values for model predicting levels of invasion. Each invasive species was modeled separately with the number of invasive plant clusters occurring within a burn transect or the mean invasive plant population size of clusters within burn transects as the response variable. *=*P*<0.05, **= *P* <0.01, ***= *P* <0.001

ANOVA Models	Model df	Error df	***Crepis tectorum***		***Melilotus officinalis***		**All focal spp.**	
			# clusters	pop. size	# clusters	pop. size	# clusters	pop. size
road presence	1	219	**27.25*** **	**8.48** **	**12.28*** **	**6.85** **	**17.94*** **	**3.62* **
road presence + road level	3	217	**10.30*** **	**3.14* **	**8.21*** **	**7.48*** **	**12.28*** **	1.38
road level + substrate severity	5	212	**7.10*** **	**2.51* **	**4.50*** **	**5.76*** **	**7.54*** **	2.03
road level + veg. severity	5	210	**5.18*** **	**2.39* **	**3.63** **	**3.55** **	**6.77*** **	2.15
road level + pre-fire stand type	5	213	**6.42*** **	1.08	**5.09*** **	**3.22** **	**7.01*** **	0.51
road level + pre-fire dom. veg.	5	213	**6.39*** **	1.75	**3.67** **	**3.22** **	**6.15*** **	1.59

Conclusions and Recommendations

The number of instances where invasive plants have moved from roadsides into burn areas remains relatively few when compared to the high abundances and well developed invasive plant seed bank in more southern areas of the United States. Only 12.5% of burned transects (a total of 27 locations) had one of our focal species moving from the roadside into burned habitat. Most of these infestations had spread less than 20 meters from the road shoulder and had small population sizes. These factors allow for easy manual control of most infestations in burned areas of our focal species. However, monitoring and hand pulling should be repeated for several years in these sites, as invasive seed banks have likely developed.

Landscape-Level Factors that Influence Invasive Plant Infestation in Burned Areas

When looking at the distribution of invasive plants over the landscape, some burn complexes appear to be more vulnerable to invasion than others. The Boundary Burn on the Steese Highway and the Chapman Creek Burn (the northernmost burn on the Dalton Highway) had limited distributions of invasive plants along the roadsides and had no instances of invasive plants moving into burned habitat. The Nenana Burn on the Parks Highway, and the two southernmost burn complexes on the Dalton Highway had widespread distribution of our focal species on the roadside, and had frequent instances of spread into burned areas.

Our data suggest that climate may drive this distribution pattern across the landscape. Both invasive plant occurrence on the roadside and movement of invasive plants into burned habitat steadily declined with increasing altitude and increasing latitude. Fewer growing degree days and changes in moisture availability likely limit the growth of invasive plants at high altitudes and latitudes. The Brooks Range offers a strong climatic buffer potentially halting the spread of our focal species into the recently burned tundra areas north of the mountains. This effect may change, however, as climate in Alaska continues to warm.

Climatic factors that appear to be driving large scale distributions of our focal species may be confounded with changes in human disturbance levels. Human use intensity tends to be greater in the lower elevation, lower latitude areas of our study. The most highly infested areas, such as the Nenana Burn, and the southernmost burn complexes on the Dalton Highway, clearly have higher levels of human activity than do the northern most burns. The Nenana Burn has permanent human residences dotted along the roadside, and lies just south of the town Nenana on one of Alaska's most frequently traveled roadways. The southern burns on the Dalton Highway contain several human disturbance areas, including a truck stop, an air strip, a pump station for the trans-Alaska oil pipeline, and several access roads to the oil pipeline in this section of the rugged trucking route that services the oil pipeline.

However, human activity and climate alone cannot explain levels of movement into burn areas. The Boundary Burn on the Steese Highway had no instances of invasives moving into burned habitat, and yet the area has been used heavily by humans for over a hundred years. Why this area remains less affected by invasive plants than the Dalton Highway burns and Parks Highway burn is left for us to research more fully. Evidence from a greenhouse study comparing burned soils from the Dalton Highway and the Steese Highway, suggests that Dalton soils were more suitable for invasive plant growth than Steese soils (Villano 2008). This effect was likely due to differences in soil pH and bryophyte cover on the soil surface (Villano 2008).

Site-Level Factors that Influence Invasive Plant Infestation in Burned Areas

The presence and abundance of invasive plants on the roadside played a very important role in determining where invasive plants occurred within burn sites. Using an additive ANOVA approach, we were able to show that both the number of successful invasion events (reflected in the number of invasive plant clusters in a transect) and the population size of invasives found in burns were influenced by the presence of invasive plants on the roadside, but only the number of clusters was influenced by the level of propagule pressure from the roadside. The number of *M. officinalis* clusters increased as the level of propagule pressure from the roadside increased. For *C. tectorum*, only low levels of abundances were necessary for several successful invasion events to occur.

Our data show that southern, moderately sloped sites with high levels of propagule pressure from the roadside had higher number of invasive plant clusters within them. The greater the propagule pressure from the roadside, the more chances an invasive species will have at a successful colonization event. In moderately sloped sites, the combination of dry enough pre-fire conditions for the surface organic layer to burn, and moist enough conditions for invasive plants to grow, may provide ideal conditions for invasive plants to colonize and spread. Sites with greater slopes will burn well, but an invading plant would likely suffer stressful germination and growing conditions. Flat sites and sites with slight slopes are often moist or boggy, which could reduce the chance of a fire burning significant portions of the organic layer.

The burn severity and the slope of a site were important in facilitating the spread of invasive plants. These two factors combined to best explain the population sizes of invasive plants in clusters within burned transects. As stated earlier, slope and severity often co-vary in boreal ecosystems and combine to create a particular soil moisture level and organic layer depth within a site after a fire. The response of invasive plants to burn severity levels was species specific. While *C. tectorum* colonized and spread best in sites that had moderate to light burn severities, *M. officinalis* colonized and spread best in high severity sites. Ultimately, the overall burn severity level of a site reflects all the environmental and vegetation variables that we measured.

Our data show that two of the most important variables for invasive plant colonization and spread in burned areas of interior Alaska are burn severity and propagule pressure. Land managers can use remotely sensed burn severity maps in conjunction with roadside invasive plant distribution maps (AKEPIC 2008) to effectively manage the spread of invasive plants in burned areas or Alaska. Susceptible burn areas to target management efforts for *C. tectorum* are moderately or lightly burned sites with the invasive present within 400 m on the roadside. Target areas for managing the spread of *M. officinalis* in burns should include high severity burn sites with dense populations of the species on the directly adjacent roadside. To prevent invasions in areas that have not yet been burned but are likely to be burn in the future, managers should consider eradicating roadside invasive plant populations adjacent to forested sites with slopes 6 to 10 degrees occurring in lower latitudes and elevations.

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