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Alaska *Melilotus* Invasions: Distribution, Origin, and Susceptibility of Plant Communities

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Abstract

Melilotus alba and *M. officinalis* were introduced to Alaska in 1913 as potential forage crops. These species have become naturalized and are now invading large, exotic plant–free regions of Alaska. We determined distributions of *M. alba* and *M. officinalis* in Alaska from surveys conducted each summer from 2002 to 2005. *Melilotus alba* and *M. officinalis* occurred at 721 and 205 sites, respectively (39,756 total sites surveyed). The northward limit for *M. alba* and *M. officinalis* was 67.15°N and 64.87°N, respectively. Both species were strictly associated with soil disturbance. *Melilotus alba* extended no farther than 15 m from road edges except where *M. alba* on roadsides met river floodplains and dispersed downriver (Matanuska and Nenana Rivers). *Melilotus* has now reached the Tanana River, a tributary of the Yukon River. Populations on floodplains were most extensive on braided sections. On the Nenana River, soil characteristics did not differ between where *M. alba* was growing versus similar areas where it had not yet reached. The pH of river soils (7.9–8.3) was higher than highway soils (7.3). Upland taiga plant communities grow on acid soils which may protect them from invasion by *Melilotus*, which prefer alkaline soils; however, early succession communities on river floodplains are susceptible because soils are alkaline.

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Introduction

High-latitude regions are not immune to colonization by alien plant species. For example, at least 6 of 173 species of the Svalbard flora (78°N) are established aliens and an additional 21–44 alien species have been collected but are not naturalized (Elven and Elvebakk, 1996; Liska and Soldan, 2004). In the subantarctic, 108 alien plant species have been catalogued, but in the Antarctic only two species, *Poa annua* and *Poa pratensis* have become naturalized (Frenot et al., 2005). Carlson and Lapina (2004b) found that 7% (39 species) of the vascular plant species in arctic Alaska are alien. In 1968, 174 of the vascular plant taxa in Alaska were recorded as alien (Hultén, 1968) and by 2006 the number had risen to 283 (Batten and Carlson, unpublished data), an increase of 63% in 38 years.

While most alien plant species in Alaska are now restricted to areas of human-caused disturbance (Carlson et al., 2004), some of these species have spread into natural landscapes. *Melilotus alba* (white sweetclover) has colonized the Stikine, Nenana, and Matanuska River floodplains (Conn and Shephard, 2003). *Melilotus alba* is also spreading in western Greenland (Polunin, 1959), the Yukon, and Northwest Territories in Canada (Tur-

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kington et al., 1978). *Melilotus* seeds are known to disperse readily in water (Turkington et al., 1978) and can remain viable in soil for at least 20 years (Stoa, 1933), suggesting the need for preventative measures to prevent colonization of new areas and long-term management to control existing populations.

Melilotus alba and *M. officinalis* were brought to Alaska in 1913 as potential forage and nitrogen-fixing crops (Irwin, 1945). Both species originated in Europe and Asia and are known to be the most winter-hardy legume forage crops for high-latitude agriculture (Klebesadel, 1992). The original introductions survived poorly (Irwin, 1945) and both *M. alba* and *M. officinalis* strains from mid-latitude regions grew as annuals (Klebesadel, 1992, 1994); however, *Melilotus* was found to shift to a biennial life cycle when grown for a number of generations in subarctic Alaska (Klebesadel, 1994).

Melilotus species can form nitrogen-fixing root nodules with *Rhizobium* bacteria. The nitrogen-fixing potential of *M. alba* has not been studied in Alaska, but *M. officinalis* was able to fix up to 100 kg N ha^{-1} in subarctic Alaska (Sparrow et al., 1993, 1995). Nitrogen-fixing species have been found to facilitate the introduction of other alien species (Vitousek and Walker, 1989), and Wolf et al. (2003) found that the number of alien species increased and native species decreased when *Melilotus* colonized montane grasslands of Colorado though this correlation was not attributed to increased soil N.

The objectives of this study were to determine the following for *Melilotus* in Alaska: (1) current distribution; (2) plant communities that have been invaded; (3) the origins of highway and river populations; and (4) soil characteristics of sites where *Melilotus* occurs. Prevention of new infestations and early detection of new *Melilotus* populations would be aided by knowing which habitats are likely to be colonized and the mechanisms of how the species are spread.

Methods

Distribution data for *M. alba* and *M. officinalis* were obtained during alien plant surveys conducted from July 2002 to September 2005 by various federal and state agencies (Table 1). Data from these surveys were entered into the Alaska Exotic Plant Information Clearinghouse Database (AKEPIC Database, 2005). Data collected for each location and alien species found were: observers, survey date, method used to determine geographic location, latitude, longitude, geographic precision, plant species code, infested area, percent ground cover, elevation, type and age of disturbance, population density, control actions, and associated vegetation type following the classification of Alaska vegetation by Viereck et al. (1992). Most surveys did not employ systematic sampling methods; the presence of alien plant species was the impetus for sampling.

DISTRIBUTION OF MELILOTUS *ALONG HIGHWAYS*

Systematic surveys of alien plant species were performed along primary and secondary roads in the Copper River, Matanuska, and Susitna Valleys in 2003 and 2004 (Carlson and Lapina, 2004a) and along the Dalton (R-11) and Elliot (R-2) highways and Chena Hot Springs Road in 2005 by the Alaska Natural Heritage Program (AKNHP). Highways that were surveyed by AKNHP in 2003–2004 included the George Parks Highway (R-3) from Anchorage to Cantwell, The Glenn Highway (R-1), the Richardson Highway from Valdez to Paxson (R-4), and the Denali Highway (R-8). Sampling locations were spaced 2–3 km apart.

To determine if exotic plant species including *Melilotus* were moving from roadsides into adjacent plant communities, Conn and Beattie (2004) studied exotic vegetation along R-2 between the Canadian border and Tok, Alaska, and Gronquist et al. (2004) employed the same methods to study exotic vegetation along the R-11 (Yukon River Bridge to Galbrath Lake). For both studies, plots (10 m $\times$ 6–10 m) were systematically located 9 km apart along the highway and were subdivided into 2 m $\times$ 10 m subplots with the long axis parallel to the highway. Percent ground cover and stem density for each species was determined in each plot. The maximum distance from the road edge that each exotic species extended was also measured. Composite soil samples (0–10 cm) were collected within the first 2 m from the road edge (Conn and Beattie study, only).

To determine whether *Melilotus* was planted along highways, Conn reviewed road construction documents at the Alaska Department of Transportation and Public Facilities (ADOT&PF) office at Fairbanks, Alaska. Reviewed were the seed specifications for revegetation, as-built files for each project, and project engineer notebooks. Several project engineers were also interviewed to determine how *Melilotus* may have been introduced to roadsides.

DISTRIBUTION AND ORIGIN OF MELILOTUS *ON FLOODPLAINS*

Early surveys for alien plant species showed that *M. alba* had invaded the floodplains of the Stikine, Matanuska, and Nenana Rivers (Conn and Shephard, 2003). Air and ground surveys were used to determine the aerial extent and population densities of *M. alba* on the Stikine and Nenana Rivers, while Matanuska River populations were studied only on the ground. Sections of the Copper, South Fork of the Koyukuk, and Tanana Rivers were also surveyed due to the existence of nearby *M. alba* populations that could have spread to the floodplains. The procedure used for all boat-based surveys was to stop at each visible *M. alba* population. Observers then walked up and down and away from the river to determine the area infested and population cover and density. The distance walked differed between locations and depended on the size of the *Melilotus* population. When *M. alba* was not visible, stops were made every 30 minutes to determine if *M. alba* or other alien species were present but not observable from the boat.

Stikine River

A boat survey was conducted by J. deMontigny and D. Rack (U.S. Forest Service) on the lower Stikine River in 2002 to investigate *M. alba* infestations within the Stikine–LeConte Wilderness Area. The surveyors determined the locations of *M. alba* infestations using GPS, and a photo-point was established on a sand island, ''The Stump Patch,'' located near the mouth of the Stikine River so that population trends and impacts could be recorded visually over time.

Conn conducted an aerial survey to determine the distribution of *M. alba* on the Stikine River and to identify its source. A fixed-wing aircraft was flown at 160 km h^{-1} on 24 July 2003 from the river mouth to Telegraph Creek, British Columbia. Overflights were made of all major tributaries of the Stikine, including the Iskut, Porcupine, Scag, and Chutine Rivers to determine if they were the origin of the *M. alba* infestation. *Melilotus alba* was in flower and had a unique light green spectral signature which was easily observed from the 153-m flight altitude. Populations were marked on a 1:500,000 aeronautical chart (Atlin AIR 5021).

TABLE 1

Surveys in which *Melilotus* was found in Alaska.

Surveyors/Agency[1]	Survey Date	Location
Park Service/Forest Service/BLM Land Surveys		
P. Bauder (NPS)	7/13/04, 7/30/04	Denali N.P. front country
P. Bauder (NPS)	7/21/04	Wrangel N.P. front country, Slana /Richardson Highway Junction
J. Delost (NPS)	6/28/04, 7/21/04	Glacier Bay N.P.
J. Hays (NPS)	7/30/04	Denali N.P. front country, Mi. 232.5 Parks Highway
P.C. McGee (USGS)	8/23/2000	Denali N.P. front country
P.C. McGee (USGS)	7/17/03, 6/8/04	Wrangel N.P. front country, Slana/Richardson Highway Junction
N. Borchert (USFS grant)	7/7/02, 7/10/02	Petersburg area
N. Borchert (USFS grant), T. Huette (USFS)	8/9/02, 7/19/03	Juneau area
N. Borchert (USFS grant)	6/3/03	Metlakatla area
B. Charnon/E. Bella (USFS)	6/14/04	Girdwood to Bird Creek bike path
T. Huette (USFS)	8/11/04	Klawock
L. Stumpf/K. Rogers (BLM)	2005	BLM Copper River Valley lands
K. Galloway, E. Uloth, C. McGee, J. Snyder, B. Charnon, M. Shephard (USFS)	2005	Kenai Penninsula roads, trails, urban areas, campgrounds
Urban Surveys		
R. Buckwalter (CES)	7/15–7/19/02	Anchorage
M. Rasy (CES)	2003, 2004, 2005	Anchorage
M. Rasy (CES)	7/8/04, 7/23/04	Alyeska Highway/Girdwood
I. Lapina/J. Mclory/M. Carlson/D. MacGlorghlin/M. Sturdy (AKNHP)/C. Dunkin (PSWCD)	7/21–25/03; 7/15–8/24/	Palmer/Wasilla/Big Lake/Knik
S. Uzzell/M. Hebert/C. Randall/M. Mueller/R. Boswell (CES)	2003, 2005	Fairbanks/Nenana/Eielson/George Parks Highway (R-3)/ Richardson Highway (R-4)
J. Snyder (CES/USFS)	7/5/2005	Valdez
Highway Surveys		
M. Shephard/ T. Huette; E. Anderson/M. Lamb (USFS)	8/5–8/6/04; 8/9/05	Haines Highway (R-7)
M. Duffy; C. Snyder/M. Rasy; M. Shephard (USFS)	8/8/98; 9/17/03; 8/16/03	Seward Highway (R-9)
M. Rasy (USFS)	8/28/03	Old Glenn Highway
M. Carlson (AKNHP)	8/19/04	Richardson Highway (R-4)
M. Carlson (AKNHP)	8/19/04	Tok Cutoff (R-1)
I. Lapina/M. Sturdy/D. Chapperl (AKNHP)/ C. Dunkin (PSWCD)	7/21–7/29/04; 8/2/04	New Glenn Highway (R-1)
I. Lapina (AKNHP)	8/25/04	R-2 (Wasilla-Cantwell)
H. Klausner (HSWCD)	8/18/04	Sterling Highway (R-1)
J. Conn/K. Beattie (ARS)	7/13–16/04	Alaska Highway (R-2)
I. Lapina (AKNHP)	8/26/05; 9/4/05	Chena Hot Springs Rd.
I. Lapina (AKNHP)	8/2–9/04; 8/23–25/05;	Elliot Highway (R-2)
M. Hebert/C. Stockdale (CES)/R. Gronquist/H.McNeel (BLM); I. Lapina (AKNHP)	8/2–9/04; 8/25/05	Dalton (R-11) Highway (start to Galbraith Lake)
River Surveys		
N.Borchert (USFS grant); J. Conn/ /K. Beattie (ARS)/M. Shephard (USFS)	7/3/02; 7/24–25/03; 8/16–17/04; 7/17–20/05	Stikine River
M. Shepard/C. Snyder (USFS)/J. Conn (ARS)	7/10/03, 9/4/03; 9/9/03	Matanuska River
J. Conn (ARS)/M. Shephard (USFS)	8/29/03; 9/2/03; 9/18–19/03; 9/1–2/04	Nenana River
J. Conn/K. Beattie/J. Morgan (ARS)	8/24–25/05	Copper River (Gakona River to Copper Center)
J. Conn; M. Hebert/K. Turner; M. Hebert/J. Moore; B. Spellman	8/29/03; 7/3–5/05; 7/29/05; 9/05	Tanana River
M. Carlson/H. Cortes-Burns	7/14–15/05	South Fork Koyukuk River

[1] NPS = National Park Service; USFS = U. S. Forest Service; CES = University of Alaska Fairbanks Cooperative Extension Service; PSWCD = Palmer Soil and Water Conservation District; AKNHP = Alaska Natural Heritage Program; HSWCD = Homer Soil and Water Conservation District; ARS = U. S. Department of Agriculture- Agricultural Research Service; UAF = University of Alaska Fairbanks; BLM = Department of Interior, Bureau of Land Management. All of the surveys were used for construction of distribution maps.

Following the air survey, a river boat was used to access *M. alba* patches on the lower river to determine geographic location, area, density, and cover, and to obtain soil samples. Five soil samples (0–10 cm) were taken at each site using a garden trowel, and these samples were combined for each site. Permanent plots were established at "The Stump Patch" to monitor long-term changes in *M. alba* populations and effects on other plant species. Three plots (0.5 m × 4 m) were spaced 2 m apart along each of two transects which were oriented east–west, parallel to the river. Stem density and percent ground cover were determined for all vascular plant species on 25 July 2003, 17 August 2004, and 20 July 2005.

Conn, Shephard, and deMontigny conducted boat-based survey in August 2004 to discover the source population of *M. alba* on the Stikine River and to collect additional soil samples to determine the characteristics of soils on which *M. alba* grows. Roads and fields in the Telegraph Creek area were searched for *M. alba*. Residents of Telegraph Creek were asked when they first noticed *M. alba* along the river.

Matanuska River

Melilotus alba populations at the Matanuska River–Old Glenn Highway intersection were first found on 10 July 2003 by M. Rassey. Conn, Shephard, and C. Snyder conducted surveys for exotic plant species by boat on 4 September 2003 along the Knik River from its intersection with the Old Glenn Highway to the New Glenn Highway (R-1) and on 9 September 2003 along the Matanuska River from the Old Glenn Highway Bridge to R-1. Five soil samples (0–2 and 2–10 cm) were obtained with a garden trowel at each stop and were composited separately for each depth at each site.

Nenana River

The *M. alba* invasion on the Nenana River was found by Roseanne Densmore (U.S. Geological Survey) in late August 2003. Conn made an aerial survey over the Nenana River from Riley Creek to where it empties into the Tanana River and then 26 km down the Tanana River on 29 August 2003. A fixed-wing aircraft flying at a speed of 163 km h^{-1} at 153-m altitude was employed for the survey. GPS waypoints were made for *M. alba* populations using the onboard aircraft GPS system. Boat surveys were conducted by Conn, Shephard, and Beattie on 2 September 2003 and 18–19 September 2003 to verify the populations identified in the aerial survey, to collect population density and cover data, and to collect composite soil samples (0–2 and 2–10 cm) for soil characterization. A similar sampling trip was made on 1–2 September 2004 by boat to determine the extent that *Melilotus* had spread on the Nenana River from the year before. Composite soil samples (0–10 cm) were collected at each stop where samples had not been collected in 2003.

Tanana River

Two trips led by M. Hebert were made on the upper Tanana River to determine whether *M. alba* had spread downriver from populations located near the river along R-2. The section of highway from Fairbanks (starting at Chena Pump Wayside) to Nenana was surveyed from 3 to 5 July 2005, and the section from the Tok River confluence to Tanacross was surveyed on 29 July 2005 using the methods employed for surveys on the other rivers. Soil samples were not obtained.

Copper River

Conn, Beattie, J. Morgan, and C. Stockdale conducted a survey by boat on 28–29 August 2005 to determine whether *M. alba* had spread onto the Copper River floodplain from riverbank populations located at the Gakona River Bridge and from populations occurring near the Gulkana River Bridge. The survey started at the Gakona River Bridge and ended at Copper Center. Our first survey stop was at the junction of the Gakona and Copper Rivers. Since *Melilotus* was not seen along the river, subsequent stops to survey were made at half-hour intervals (10–15 km).

South Fork Koyukuk River

M. Carlson and co-workers examined the South Fork of the Koyukuk from 10 km east of the confluence with the Jim River by boat from 14 to 15 July 2005 to determine whether *M. alba* had spread downriver from known sites where it occurs where the South Fork and Jim River are bisected by the Dalton Highway (R-11). Stops were made at roughly half-hour intervals and at some other sites with exposed gravel bars that appeared to be likely habitat for *Melilotus*.

SOIL ANALYSIS

Proportions of sand, silt, and clay in the samples were determined using the Bouyoucos hydrometer method (Gee and Bauder, 1986). For P and K analysis the Mehlich-3 extraction method (Tran and Simard, 1993) was employed. NO_3 and NH_4 were measured using the 2 N KCL extraction method (Dahnke, 1980). Soil pH and conductivity were measured with an electrode and 1:1 soil:water slurry (Dahnke, 1980).

DATA ANALYSIS

The Statistical Analysis System (Institute Inc., 2000) was used for data analysis. To determine if soils data (pH, conductivity, % OM, texture, and nutrients) from the two soil depths (0–2 cm and 2–10 cm) where samples were collected along the Nenana and Matanuska Rivers differed, the data were analyzed using PROC GLM with a nested analysis of variance (ANOVA) model. Rivers were main effects and soil depths were nested. Since none of the soil variables was influenced by sampling depth, the data from the 0–2 cm and 2–10 cm depths were averaged. Soil data from the Nenana, Matanuska, and Stikine Rivers were combined with soil data obtained from roadside vegetation studies conducted by Conn and Beattie along R-2 (0–10 cm sampling depth) to determine whether the rivers and highways differed in soil characteristics. A one-way ANOVA was used for the analysis. *T*-tests were used to determine whether soil characteristics differed between sites on the Nenana River where *M. alba* was growing versus similar sites where it did not occur. This test was not used for other rivers due to the much smaller number of soil sample locations.

PROC CORR of SAS was used to determine whether soil variables were correlated with *M. alba* ground cover. The combined soils data from the three rivers and highway studies and *M. alba* ground cover for each site were employed in the analysis.

A one-way ANOVA was used to determine whether density and cover of species in permanent plots at the "Stump Patch" (Stikine River) changed over the three-year measurement period.

The GPS locations of *M. alba* and *M. officinalis* within Alaska were plotted on a geographic information system base layer (State of Alaska Department of Transportation) using ArcView 9.1 (ESRI, 2005). Distribution maps of *Melilotus* on the Stikine, Matanuska, and Nenana Rivers were also made using ArcView plotting GPS locations of populations on LANDSAT 7 imagery obtained for each river.

Results

GENERAL DISTRIBUTION OF MELILOTUS

Melilotus alba and *M. officinalis* occurred in the boreal and maritime ecological zones (Nowacki et al., 2002) of Alaska. A total of 721 *M. alba* populations were found throughout Alaska by various survey teams. It is currently distributed in urban centers, along roads, and on the floodplains of the Stikine, Matanuska,

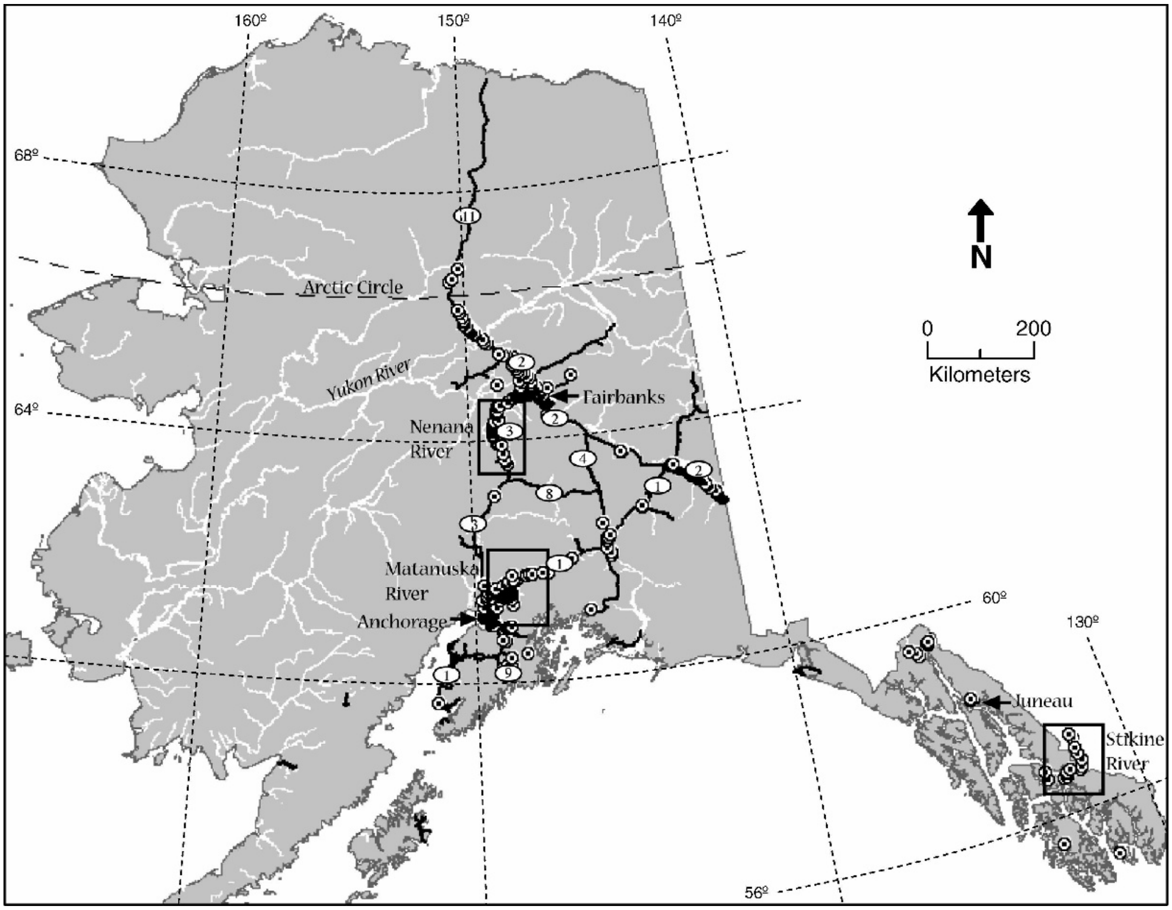

FIGURE 1. Distribution of *M. alba* in Alaska. GPS locations for *M. alba* populations found in surveys made during 2003–2005 are shown.

Lower Knik, and Nenana Rivers (Fig. 1). It was found above the Arctic Circle as far north as 67.15°N along the Dalton Highway (R-11) and at elevations to 691 m.

Melilotus officinalis was encountered less frequently (205 populations) and was found mainly in urban centers and along roads in south-central Alaska and at Fairbanks (Fig. 2). A few populations were found north of the Alaska Range, with its furthest north population at the University of Alaska in Fairbanks (64.87°N) and highest elevation (492 m) near the entrance of Denali National Park and Preserve. Both species of *Melilotus* appear to be absent from roadless regions of the state. *Melilotus* was found only where soils had been disturbed (Table 2). An obvious difference between the two species was that *M. alba* was found much more often on river-disturbed soils than was *M. officinalis* (10.3% of sites vs. 1.0%, respectively), whereas *M. officinalis* was almost always found along roads.

DISTRIBUTION, AND SPREAD OF MELILOTUS *ALONG HIGHWAYS*

While 80% of *Melilotus* populations were found on soil imported to build roads (Table 2), there were obvious differences in distribution of *Melilotus* between highways (Figs. 1 and 2). Highways with large *Melilotus* populations were the R-2 (Canada to the Tanana River and Fairbanks to Eielson Air Force Base), R-3 (Fairbanks to Healy), and R-2/R-11 (from Fairbanks to Jim River). On the other hand, roads, such as the Denali Highway (R-8), had little to no *Melilotus* present.

ADOT&PF highway construction records failed to conclusively show that *Melilotus* was intentionally planted on the infested highways. Usually, the only information regarding species planted in these documents was seed specifications in bid documents and these specifications were not a part of bid packages for projects built before 1970. The project records did not include receipts of seed purchased or copies of seed tags. However, there were several documents that suggested that *Melilotus* could have been used for revegetation between 1978 and 1986. "Dutch white clover" was listed in the seeding specifications for two highway reconstruction projects completed between 1984 and 1985 along the Alaska Highway (R-2, mile 1235–1256). Also, a change order was found that specified "white clover" for planting as part of reconstructing R-3 between Nenana south to the Rex Bridge (1978). Dutch white clover and white clover are varieties of *Trifolium repens*, but without specifying the scientific name, contactors may have bought a seed mix containing white sweetclover (*M. alba*).

The length of *Melilotus* patches along highways was variable. Sometimes single plants or small patches were encountered with long distances between patches. Continuous stretches of *Melilotus* were also encountered, especially along R-3 (the Parks Highway between Fairbanks and Denali National Park); R-2/R-11 (between Fairbanks and the Jim River); and R-2 (Canada to the Tanana River and Fairbanks to Eielson Air Force Base).

The average distance from road edge to the last *Melilotus* individual was 6.0 m in the study along the Alaska Highway (R-2) study and 4 m in the study along the Dalton Highway (R-11). The farthest that *M. alba* grew from the road edge was 15 m, and it was not found in undisturbed areas. The roadside study plots were adjacent to a wide variety of plant communities including black spruce forest (*Picea mariana*), white spruce forest (*Picea glauca*),

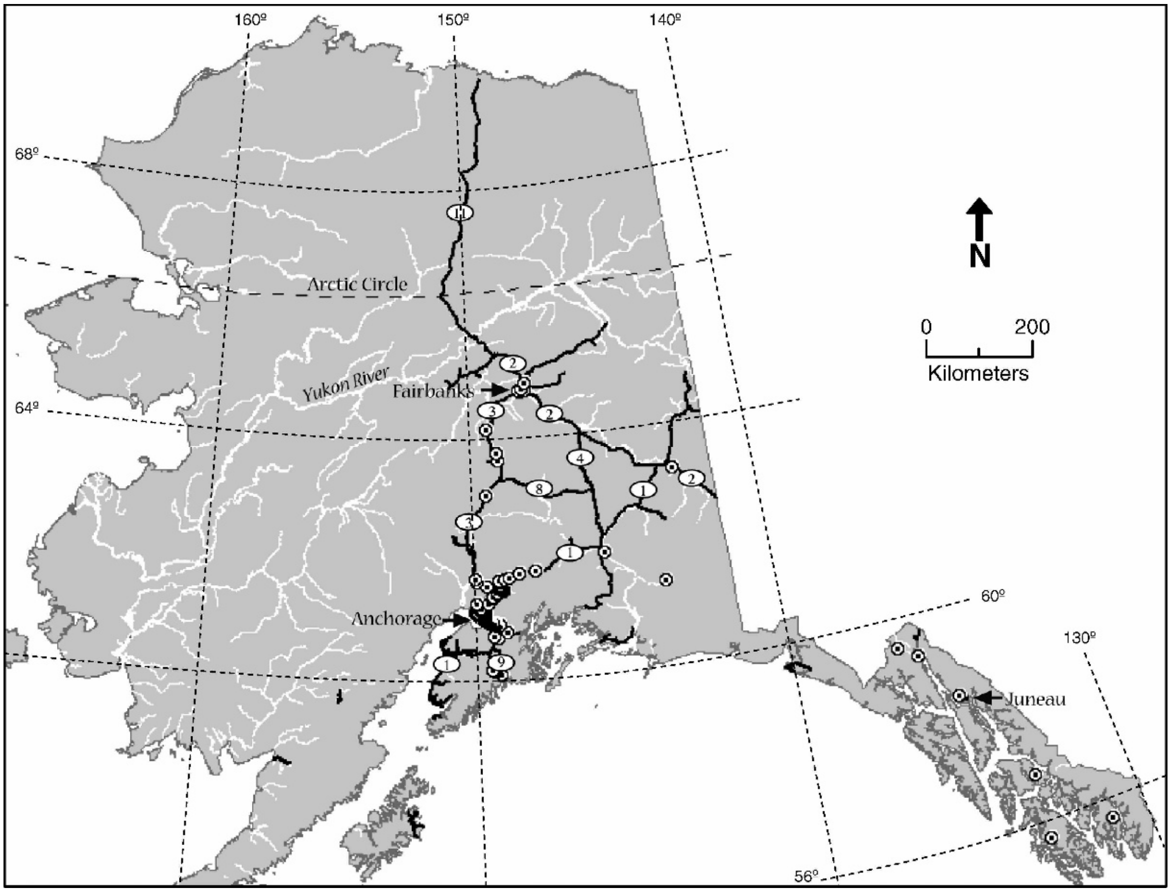

FIGURE 2. Distribution of *M. officinalis* in Alaska. GPS locations for *M. officinalis* populations found in surveys made during 2003–2005 are shown.

aspen forest (*Populus tremuloides*), paper birch forest (*Betula papyrifera*), mixed broadleaf forest, mixed broadleaf/white spruce forest, and dwarf birch (*Betula nana*)/sedge (*Carex* spp.) wetlands.

DISTRIBUTION OF MELILOTUS *ON FLOODPLAINS*

Stikine River

During the 2003 aerial survey, *M. alba* was found mainly on sand islands near the mouth of the river or on braided sections of the river. The largest populations were at confluences with steep-gradient, glacial-fed tributaries such as the Scag and Chutine Rivers (Fig. 3). The invasion appeared to end just below Telegraph Creek, upriver of the confluence with the Chutine River. *M. alba* had not colonized any of the major Stikine tributaries. Boat-based surveys in 2003–2005 found additional small *M. alba* populations associated with localized river erosion. *Melilotus alba* was not found under dense canopies formed by *Alnus* spp. (the predominate canopy species on newer soils) or *Populus balsamifera* (the major canopy species on higher/older deposits).

We searched for, but did not find *M. alba* in agricultural fields or along roads in the vicinity of Glenora and Telegraph Creek and at the abandoned Hudson Bay Company site which was surrounded by agriculture during the Klondike Gold Rush. Two small *M. alba* populations were found growing along the road

TABLE 2

Association of *Melilotus* with various disturbance types in Alaska.

Disturbance type	*M. alba* sites (Number)	*M. alba* sites (%)	*M. officinalis* sites (Number)	*M. officinalis* sites (%)
Fill importation for roads or railroads	576	79.9	163	79.5
Other mechanical disturbance	45	6.2	26	12.7
Material extraction	2	0.3	10	4.9
Mechanical brush cutting	3	0.4	0	0
Off road vehicle disturbance	3	0.4	0	0
Plowing	2	0.1	1	0.5
Trampling	11	1.5	3	1.5
Grazing	1	0.1	0	0
River disturbance	74	10.3	2	1.0
TOTAL	721		205	

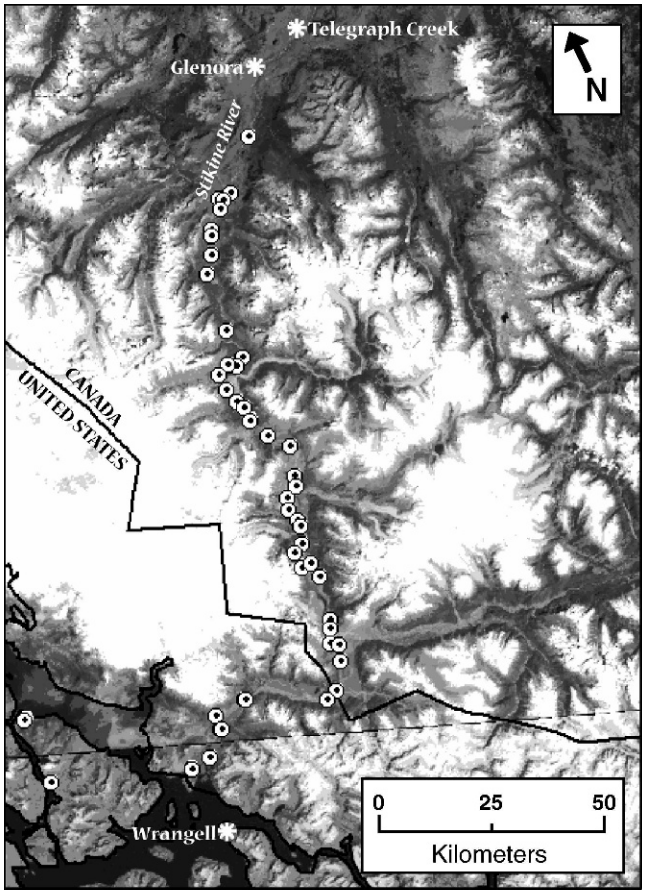

FIGURE 3. Distribution of *M. alba* on the Stikine River, located in southeast Alaska and western Canada. GPS locations of populations found in surveys conducted during 2003–2005 were plotted on LANDSAT 7 imagery obtained 5 August 1999 and 10 August 2001 (image center, latitude 57.1167°N, 131.5667°W).

connecting Telegraph Creek to the Cassiar Highway (Highway 37). These populations were approximately 0.3 km from the Stikine River. Francis Gleason (age 74), a long-term resident near Telegraph Creek, recalled first seeing *M. alba* as a small boy downriver from Telegraph Creek. He described its smell and that he was impressed with all of the bees around it. His observations suggest *M. alba* has been on the river since before 1935–1940.

Density and cover of *M. alba* in permanent plots located at "The Stump Patch" (Stikine River) were measured during each year from 2003 to 2005. Individuals at this location were only of one age class, alternating between first-year and second-year plants. When the site was first visited in 2002, the plants were all second-year individuals. A one-way ANOVA showed that the density and percent cover of *M. alba* and several other species changed from 2003 to 2005. *Melilotus alba* density declined from 2003 to 2004, then drastically fell in 2005 (Table 3) due to insect defoliation (insect not identified). The decline of *M. alba* density in 2004 was probably due to self-thinning since it was in its second-year life stage and percent cover was high. *Equisetum palustre* density declined with the increase in *M. alba* cover in 2004. Density of *Leymus mollis* increased significantly in 2005 as the density and cover of *M. alba* declined; However, cover of *E. palustre* and *L. mollis* did not increase significantly. There were no significant trends in density or cover of *Salix* or *Lathyrus maritimus*.

Matanuska River

Large (>1 km^2) *M. alba* populations were found downstream from the Old Glenn Highway Bridge to the terminus in Cook Inlet (Fig. 4). General field observations showed that populations were most extensive on river bars in braided sections of the river (Fig. 4). This portion of the Matanuska River experiences strong adiabatic winds from the Knik Glacier, which erodes fine soil particles and leaves older terraces that are cobbly and pavement-like. *Melilotus alba* densities were much lower on cobbly surfaces than in areas with sandy soils (J. Conn, personal observation).

Nenana River

Extensive *M. alba* populations (some patches > 1 km^2) extending 13 km downstream from the Rex Bridge were found during the 2003 aerial survey (Fig. 5). Two small populations with only a few plants were found 5 km above the Rex Bridge. A mixed population of *M. alba* and *M. officinalis* was found growing next to the river at the Healy Clean Coal Power Plant. We did not find *Melilotus* on the river above Healy or further than 13 km below the Rex Bridge. Boat-based surveys confirmed the sightings and distribution found in the aerial survey. In 2004, we found that *M. alba* had colonized new sites extending another 32 km downriver to the confluence of the Nenana River with the Tanana River (Fig. 5). New populations were also found between the Healy power plant and the Rex Bridge. *Melilotus alba* densities were greater in sandy rather than cobbly soil (J. Conn, personal observation).

Tanana, Copper, and South Fork Koyukuk Rivers

Melilotus was not found growing on the Tanana River floodplain despite the probable input of seed from the Nenana River and from populations growing adjacent to the Tanana River at several locations along highways. Similarly, *Melilotus* was not found on the Copper River floodplain or South Fork of the

TABLE 3

Density and cover of *M. alba* and associated species at "The Stump Patch," Stikine River, Alaska.

	Density (stems m^{-2})					Ground cover (%)					
Year	*M. alba*[a]	*Leymus mollis*	*Equisetum palustre*	*Salix* sp.	*Lathyrus maritimus*	*M. alba*	*Leymus mollis*	*Equisetum palustre*	*Salix* sp.	*Lathyrus maritimus*	Total
2003	474a	13a	318a	0.7	0.4	46.7a	8.3	9.3a	0.2	0.1	65.7a
2004	164b	13a	89b	0.3	0.5	76.7a	11.0	4.0b	0.2	1.0	92.8a
2005	14b	29b	157b	0.3	0.4	0.1b	12.7	1.7c	0.2	0.4	15.5b

[a] Values within a column with the same letter are not significantly different at the 0.05 level using Tukey's mean separation test.

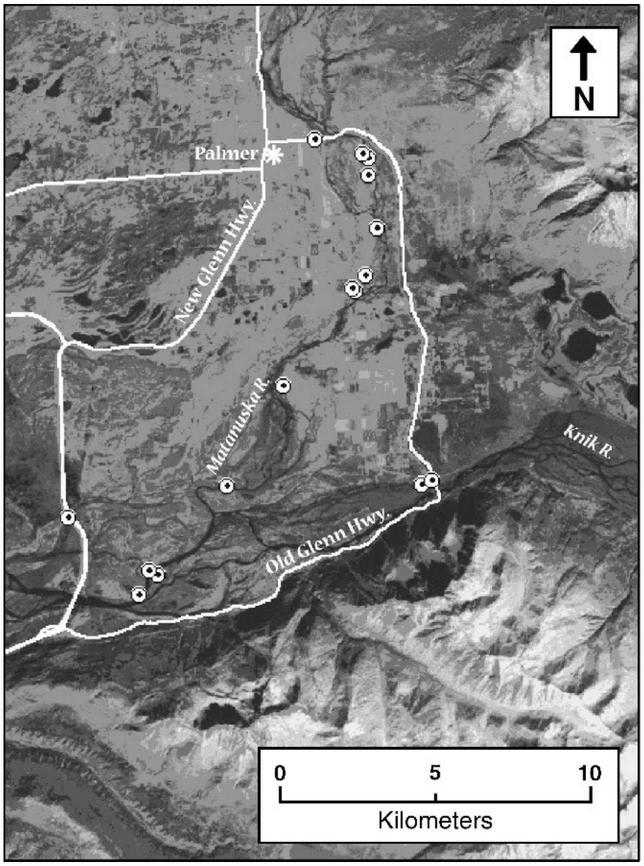

FIGURE 4. Distribution of *M. alba* on the Matanuska River, east of Anchorage, Alaska. GPS locations of populations found in surveys conducted in 2003 were plotted on LANDSAT imagery obtained 30 July 2002 (image center, latitude 61.5250°N, 149.1167°W).

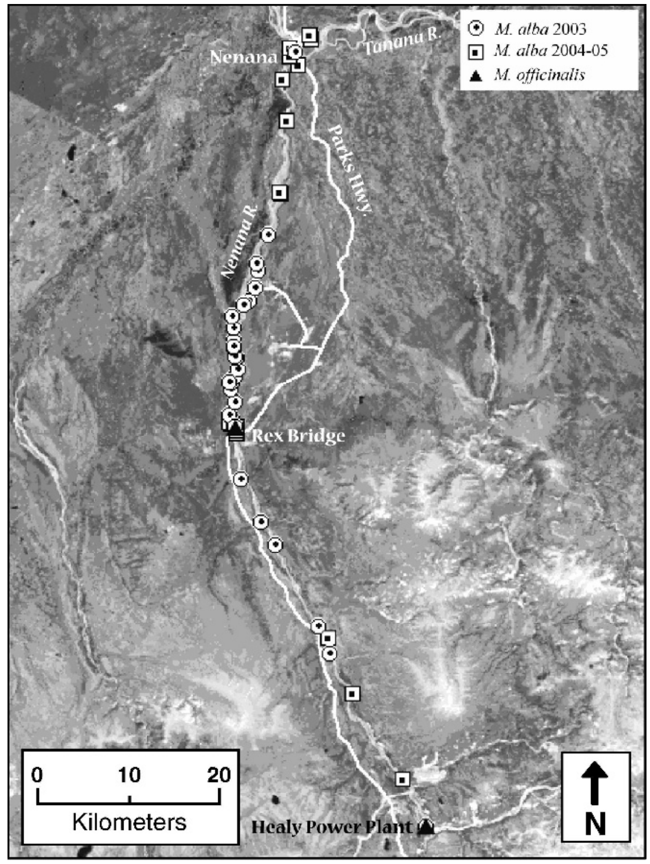

FIGURE 5. The distribution of *Melilotus* on the Nenana River, north of Denali National Park, Alaska. GPS locations of populations of *M. alba* and *M. officinalis* found in surveys conducted in 2003–2004 were plotted on LANDSAT imagery obtained 27 May 2002 image center, latitude 64.2167°N, 149.0040°W).

Koyukuk River even though *M. alba* was growing next to the Gakona River near its confluence with the Copper River, and along the Dalton Highway (R-11) where the South Fork Koyukuk and its tributaries are crossed by the highway.

SOIL CHARACTERISTICS

Analysis of variance showed that soil characteristics were different between rivers and the highway roadside (Table 4). Soil pH was significantly lower along the roadside (pH = 7.3) than on the floodplains (mean pH = 7.9–8.3). Electrical conductivity, a measure of salt content, was significantly greater in the Stikine River soils (0.24 dS m^{-1}) than the Nenana, Matanuska, and roadside samples (0.16, 0.17 and 0.17 dS m^{-1}, respectively). All soils contained at least 65% sand and were low in clay though the Matanuska River soils had significantly more clay than soils from Nenana and Stikine River soils (5.5% vs. 1.6 and 2.4%, respectively). Stikine River soils were higher in NH_4, NO_3, and K than soils from the other rivers and the highway soils. Organic matter levels and total percent carbon were highest in highway soils and were significantly higher than Matanuska and Nenana River soil.

No significant differences in soil characteristics were found between Nenana River sites with and without *M. alba* (*t*-tests, $p \leq 0.05$). Correlation analysis of soil variables from the Stikine, Matanuska, and Nenana Rivers and highway sampling sites with *M. alba* ground cover failed to show any significant correlations between *M. alba* cover and any of the soil variables measured.

Discussion

DISTRIBUTION OF MELILOTUS

Melilotus in Alaska grows in a diverse range of climatic conditions from southeastern Alaska to the Brooks Range (55.34°N to 67.15°N). For example, it occurs at Ketchikan, which receives 394 cm of precipitation (NOAA, 2003) and where temperatures are mild (7.2°C annual mean), and in the interior of Alaska it grows where yearly precipitation can be as low as 17 cm and average annual temperature are only −3.3°C (Tok, Alaska).

Melilotus alba and *M. officinalis* are well adapted to roadsides in Alaska but are more common along some highways than others. Moreover, sudden starts and stops in its distribution along roadsides suggest that *Melilotus* was planted along the roadside. For example, on the Alaska side of the Canada–Alaska border, there were extensive *M. alba* stands that stretched into Alaska along R-2, while on the Canada side of the highway it did not occur. Proof that *Melilotus* was intentionally planted is lacking, however. *Melilotus* could have been planted unintentionally by purchase of the wrong seed or through contamination of the specified seed. While highway engineers require extensive quality control of physical materials used for road building, quality control for the biological materials (seeds) used for revegetation along roads is nearly nonexistent. Many weed problems could be prevented if seed lots to be used for revegetation were tested for weed contaminants prior to planting.

TABLE 4

Differences in soil characteristics between rivers and highways with *M. alba*.

Site	n	pH[a]	Electrical conductivity (dS m^{-1})	Organic Matter (%)	Sand (%)	Clay (%)	Silt (%)	NH_4 (ppm)	NO_3 (ppm)	P (ppm)	K (ppm)	Total C (%)	Total N (%)
Matanuska R.	8	8.3a	0.17a	1.0a	65a	5.5a	30a	1.1a	1.4a	5.1a	41.4ab	0.5a	0.01a
Nenana R.	8	7.9a	0.16a	0.5a	77a	1.6b	21a	0.5a	0.4a	4.6a	39.8a	0.3a	0.02a
Stikine R.	7	8.0a	0.24b	1.3ab	66a	2.4ab	32a	2.7b	13.3b	3.7a	67.0b	0.7ab	0.28a
Alaska & Parks Highways	8	7.3b	0.17a	3.1b	74a	3.6ab	22a	0.7a	1.0a	9.0b	62.3ab	1.8b	0.527a
Range (all sites)	31	6.6–8.7	0.6–0.45	0.3–8.4	26–90	0.5–13.0	9–70	0.1–3.9	0.1–36.9	4–14	23–113	0.2–4.9	<0.01–0.165

[a] Values within a column with the same letter are not significantly different at the 0.05 level using Tukey's mean separation test.

The likely origin of *M. alba* on the Matanuska and Nenana Rivers is from populations growing along highways that intersect or run alongside them. For example, populations of *M. alba* occur downriver from the Old Glenn Highway bridge, but not upriver. Roadside populations were probably also the origin for the main infestation of *M. alba* on the Nenana River. Aerial and ground surveys in 2003 found no *M. alba* populations immediately upriver from the Rex Bridge, but extensive populations extended on the floodplain 13 km downriver. Flood events could easily carry seed downriver since *Melilotus* is known to disperse readily in water (Turkington et al., 1978).

The origin of *M. alba* on the Stikine River is not as obvious. It did not reach the Stikine through tributaries and its distribution stops just short of Telegraph Creek, British Columbia. We did not find it in Telegraph Creek or Glenora. According to local knowledge (F. Gleason, personal communication), *M. alba* has been on the Stikine River just downstream from Telegraph Creek since at least 1935–1940. This time frame predates the Cassiar Highway (finished 1972), the only road crossing the Stikine River upstream, so it is unlikely that roadside populations were the source of *M. alba* on the Stikine floodplain. Telegraph Creek was the limit of navigation for stern wheel ships and was a stopover for gold miners on their way to the Cassiar and Klondike gold fields (Loken, 1979). *M. alba* may have been grown at Glenora to feed draft animals used for transporting supplies. *M. alba* may have escaped from these fields onto the Stikine River floodplain.

SUSCEPTIBLE SUBSTRATES AND COMMUNITIES

Both *Melilotus* species are known to prefer well-drained soils that are alkaline or only slightly acidic (Smith et al., 1986). Sparrow et al. (1993) evaluated the biomass production of *M. officinalis* as a crop at Delta Junction, and Fairbanks, Alaska. Biomass yields of *M. officinalis* at Fairbanks (pH = 7.2) were 2.3 times greater than at Delta Junction (pH = 6.3). In our study, both roadside and river floodplain soils were neutral to alkaline. Roadside soils are mainly sands and gravels mined from the floodplain or from upland rock quarries; however, upland soils away from river floodplains in Alaska tend to be acidic which would not favor *Melilotus*. Van Cleve et al. (1983) measured soil characteristics of major taiga plant communities in Alaska and found that soil pH levels of upland mineral soils ranged from 4.5 (black spruce) to 5.6 (paper birch).

The forest fires of 2004 and 2005 burned the first and third greatest areas of forest in Alaska's recorded history. Surveys of roads with known *Melilotus* populations adjacent to burned areas by one of the authors (Gronquist, 2005) showed that *Melilotus* had generally not colonized the newly exposed mineral surfaces, though several individual plants were found 15 m from the road edge (R-11) adjacent to severely burned aspen-spruce forest. Except for this isolated instance, the authors have found that *Melilotus* does not colonize upland soils. The probable reason is that these soils may be lower than optimum pH for *Melilotus* growth. Dyrness and Norum (1983) found that the pH of mineral soil in an upland black spruce forest only increased from 3.8 to 4.0 after a severe fire, suggesting that fire will not increase pH up to optimal levels for *Melilotus* growth.

Since the Nenana River feeds the lower Tanana River and hence the Yukon River, it is important to know whether *M. alba* will spread further into these river systems. Surveys on the Tanana River in 2003 (aerial) and 2005 (boat) failed to find it despite the high probability of seed entering from the Nenana River and *Melilotus* populations that were upstream along roads next to the river.

It is useful to examine whether the soils of the Tanana and Yukon Rivers are suitable for growth of *Melilotus*. Viereck et al. (1993) described primary succession sequences on the Tanana River floodplain and Marion et al. (1993) studied associated changes in the chemical environment. Of the 12 successional stages described, *M. alba* or *M. officinalis* could possibly occur in stages II–III. Stage I floods frequently each year and no vegetation establishes. Stage II occurs on higher terraces and, though usually flooding several times a year, is dominated by scattered willows and herbs. Stage III occurs on terraces that are 2–5 years old that are high enough that flooding usually occurs once a year or not at all. Stage IV has a closed canopy dominated by alder and willow. *Melilotus* species have not been seen in closed stands in Alaska and are thought to be shade intolerant (Turkington et al., 1978). The soils of the early stages of succession are characterized by alkaline soils (pH $>$ 7.7) and salt-affected surfaces resulting from capillary rise and salt precipitation caused by evaporation (Van Cleve et al., 1993). The soluble salts were mainly associated with the silt texture size fraction and were found to increase during the early stages of succession as silt layers build up and terraces increase in height (Marion et al., 1993). Electrical conductivity measurements of 1.13–3.03 dS m^{-1} were found in soils from Stage III sites. Soil salt contents in this range can decrease phosphorus, Fe, Zn, and Mn availability and seed germination can be inhibited by the high osmotic potentials (Van Cleve et al., 1993).

Though *Melilotus* has thus far been found mainly on sandy soils in Alaska, these species are known to grow on a wide range of soil textures including clay, loam, sand, and gravel (Turkington et al., 1978). Both species are well known for their salt tolerance and affinity for calcareous soils. Evans and Kearney (2003) evaluated *M. alba* as a forage crop for saline soils in southwestern Victoria, Australia, and it had high productivity on neutral to alkaline pH soils with electrical conductivities up to 5 dS m^{-1}. According to Kotuby-Amacher et al. (1997), *Melilotus* has a salinity threshold of 4 dS m^{-1}, and experiences a 10% yield loss at 6 dS m^{-1}. Thus, it appears that the texture, pH, and salinity of soils on the Tanana or Yukon Rivers are not obstacles to colonization by *Melilotus*. However, neither species can withstand prolonged flooding. Weekes and Cavers (in Turkington et al., 1978) found less than 10% of plants of either species survived a 5-day immersion. We have seen *M. alba* survive mild flooding along the Nenana River. Flooding on this high-gradient, highly dissected floodplain was shallow, widespread and did not last more than a few days. All of the extensive *Melilotus* infestations on Alaska floodplains found so far have been on the broad, braided portions of the rivers, with only small patches (<10 m^2) associated with newly exposed soil occurring in channelized sections of river. The Tanana floodplain is more channeled, bare soil is less abundant, and floods are longer in duration compared to the Matanuska, Nenana, and Stikine Rivers. The inability of *Melilotus* to withstand long durations of immersion could limit spread into the Tanana and Yukon River floodplains.

The mechanisms of colonization and succession on the Tanana River floodplain are stochastic in nature and depend on seed rain, flood events, silt deposition, weather patterns, and relative growth rates of colonizing species (Walker and Chapin, 1986; Walker et al., 1986). The right combination of flooding to disperse seed from populations on the Nenana River to alluvial deposits above the usual flooding height along the Tanana River may not have happened yet. The rapid development of genotypes adapted to high latitudes by natural selection and current broad ecological tolerances, however, suggests that the safest strategy is to limit seed dispersal to new areas. Unfortunately, seed of *Melilotus* is already entering these ecosystems and its ability to colonize the Tanana and Yukon floodplains will soon be revealed.

IMPACTS OF MELILOTUS

We do not know the full impacts of *Melilotus* on floodplain communities in Alaska. *Melilotus officinalis* is known to produce high amounts of biologically fixed N in the subarctic (Sparrow et al., 1995). Increased nutrient availability can facilitate invasion by other alien species that are not adapted to low nutrient levels (Maron and Connors, 1996) or shift the pattern of plant dominance during succession (Tilman, 1987). A number of studies have examined the effects of symbiotic nitrogen fixation associated with *Alnus* spp. on primary succession in Alaska. *Alnus* can inhibit or facilitate the growth of individual species depending on site conditions, species, and life stages during the interaction (Callaway and Walker, 1997; Chapin et al., 1994; Fastie, 1995; Walker and Chapin, 1986; Walker et al., 1986; Densmore, 2005). However, Wolf et al. (2003, 2004), working in montane grasslands in Rocky Mountain National Park, Colorado, found lower N availability and mineralization and higher C:N ratios in the patches invaded by *Melilotus* than outside the patches. Interestingly, despite the lower soil fertility, more non-native species were found in the invaded patches. On the Nenana River, the presence of *M. alba* did not change soil NH_4, NO_3, or total N content (comparing soil samples with *Melilotus* to soil samples without). At ''The Stump Patch'' a crash in *M. alba* populations in 2005 due to insect defoliation was not accompanied by increases in cover by *L. mollis*, *E. palustre*, or *Salix*.

More research is needed to determine the effects of *Melilotus* on other plant species where it has colonized. A large proportion of Alaska's rare vascular plants occur along river corridors; the narrow endemics *Astragalis williamsii* and *Salix setchelliana* grow where dense patches of *M. alba* have become established and it is unknown whether *M. alba* is having a detrimental effect on these species. The effects of *Melilotus* on pollinators also needs to be examined. Both *M. alba* and *M. officinalis* are attractive to bees and could be competing for or attracting additional pollinators. Since *Melilotus* seed can persist in soil for 20 years or more (Stoa, 1933) eradication of new infestations will be difficult.

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