# Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska

**Eric Klein, Edward E. Berg, and Roman Dial**

**Abstract:** This study documents the scale and intensity of drying over the last half century in the Kenai Lowlands of south-central Alaska. Using historical aerial photos and field sampling of wetlands, including muskegs, kettle ponds, and closed and open basin lakes, we present data on drying and successional changes in woody vegetation between 1950 and 1996. The results of this study suggest that the Kenai Peninsula is becoming both woodier in its vegetation and drier. A regional analysis of 1113 random points indicated increased forest cover and decreased open and wet areas in both burned and unburned areas between 1950 and 1996. A census of water bodies in three subregions indicates that almost two-thirds of water bodies visited show some level of decrease in spatial area. Over 80% of field sites visited have experienced some level of drying, where vegetation transects indicate substantial invasion into former lake beds by facultative upland plants. These results are consistent with a regional change in climate that is both warming and drying as documented in Kenai and Anchorage weather records.

**Résumé :** Cette étude documente l'étendue et l'intensité de l'assèchement au cours du dernier demi- siècle dans les basses terres de la presqu'île de Kenaï qui est située dans le centre sud de l'Alaska. À l'aide d'anciennes photographies aériennes et d'un échantillonnage des terres humides, incluant les muskegs, les kettles transformés en étangs et les lacs qui occupent des cirques glaciaires ouverts ou fermés, les auteurs présentent des données sur l'assèchement et les changements dans la succession de la végétation ligneuse entre 1950 et 1996. Les résultats de cette étude indiquent que la presqu'île de Kenaï devient plus sèche et que sa végétation compte plus d'arbres. Une analyse régionale de 1113 points au hasard révèle une augmentation du couvert forestier et une diminution des zones humides et dégagées tant dans les secteurs brûlées que non brûlées entre 1950 et 1996. Un relevé des plans d'eau dans trois sous-régions indique que près des deux tiers des plans d'eau visités ont vu leur superficie diminuer. Plus de 80 % des stations visitées ont connu un certain degré d'assèchement et des transects dans la végétation indiquent une importante invasion d'anciens lits de lac par des plantes qui se développent facultativement en milieu sec. Ces résultats sont consistants avec un changement dans le climat de la région qui se réchauffe et devient plus sec tel que l'indique des données météorologiques pour Anchorage et la presqu'île de Kenaï.

[Traduit par la Rédaction]

## Introduction

Global temperatures have increased by about 0.6 °C over the past 100 years (Watson 2001). The rate of temperature increase from 1976 to the present has been double that from 1910 to 1945 and thus greater than at any other time during the last 1000 years (Watson 2001). Different indicators of a warming trend have been documented across the globe. Parmesan and Yohe (2003) recently compiled various global studies on changes in species' range and phenology and found highly significant, nonrandom patterns of change in agreement with observed climatic warming of the 20th century. Their comprehensive study found range limits of species have moved northward an average of 6.1 km per decade and spring events have increased 2.3 days per decade, both significantly in accord with predictions posed by climate change. Worldwide, a disproportionate amount of evidence for global climate change has come from Alaska. For example, glacial recession (Arendt et al. 2002) and vegetative change (Sturm 2001; Silapaswan et al. 2001) have been documented using photos and map coverage from the middle of last century to the present. Similarly, arctic aerial photos (Stow et al. 2004) indicated shrub expansion as well as shifts in water body coverage. Alaska may be unique in the world for its application of state-of-the-art mapping and photogrammetric technology to document natural environments essentially undisturbed by local human use for the last 50 years. Mapping and photogrammetric projects beginning in the 1940s and continuing to the present have captured these essentially undisturbed landscapes. Thus Alaska offers an opportunity to study the possible impacts of climate change with minimal noise due to local changes in land use, population growth, and habitat fragmentation.

Besides the published work on glacial retreat in south-central Alaska (Arednt et al. 2002) and woody shrub spread in northern Alaska (Sturm et al. 2001; Silapaswan et al.

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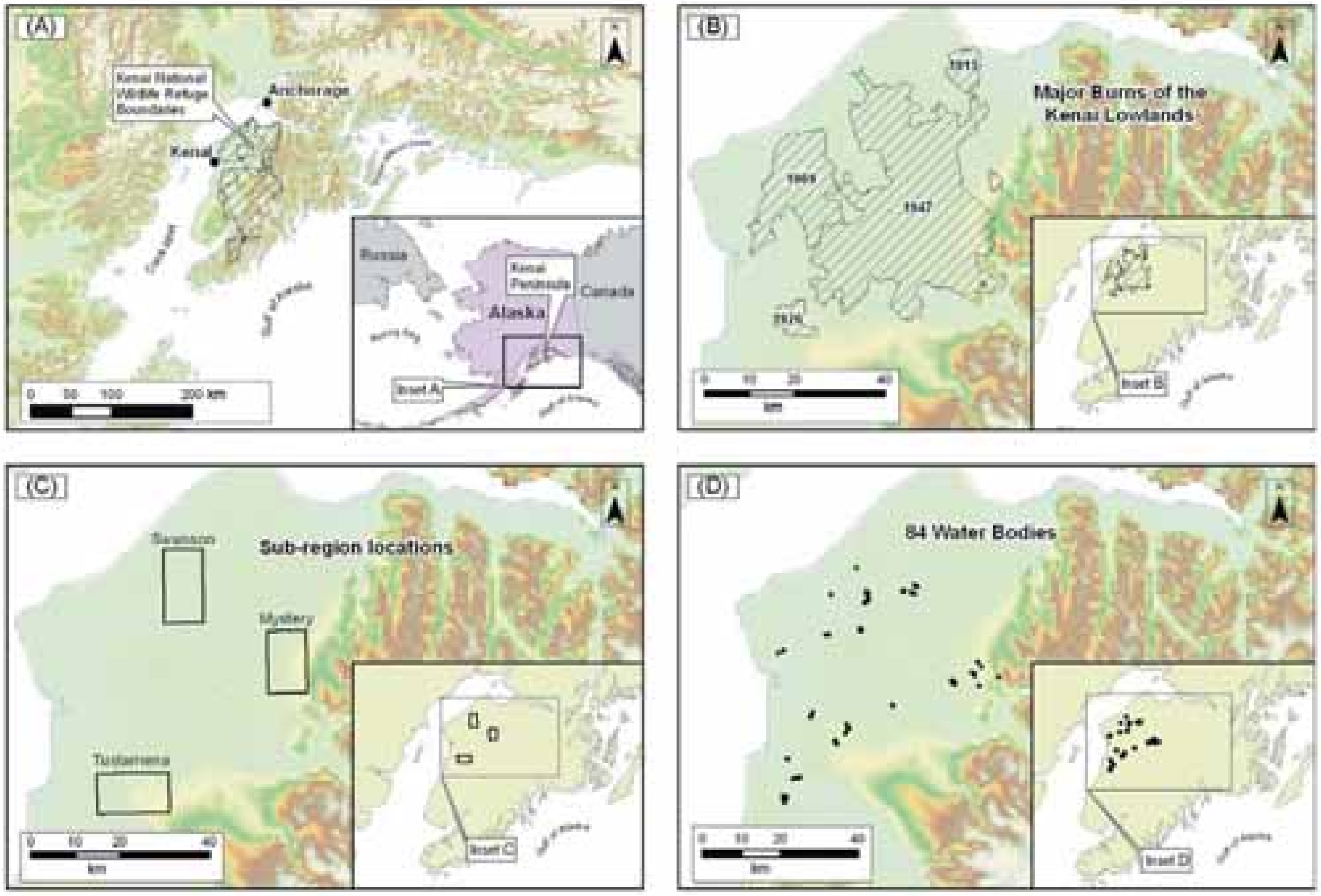
**Fig. 1.** (A) Kenai Peninsula and Kenai National Wildlife Refuge. (B) Major burns. (C) Subregion locations. (D) Water body site visits ($n$ = 84).




2001; Stow et al. 2004), there is also anecdotal evidence for climate change elsewhere in Alaska, particularly in the Kenai Peninsula. Rising tree lines in the Kenai Mountains and drying muskegs, kettle ponds, and closed basin lakes (Berg personal observation 2003) seem to corroborate weather data revealing decreasing water balance and increasing temperatures (National Climate Data Center 2003). Moreover, it has been shown that a decrease in the water level of boreal peatlands can initiate succession from a wetland to upland habitat (Jukaine and Laiho 1995).

As a result of increasing temperatures, Alaskan wetlands could be drying and succeeding to upland habitat. This study documents the scale and intensity of drying over the last half century in the Kenai Lowlands of south-central Alaska. Using historical aerial photos and field sampling of wetlands, including muskegs, kettle ponds, and closed and open basin lakes, we present data on drying and successional changes in woody vegetation between 1950 and 1996 that are consistent with regional drying that is due to climate change.

## Materials and methods

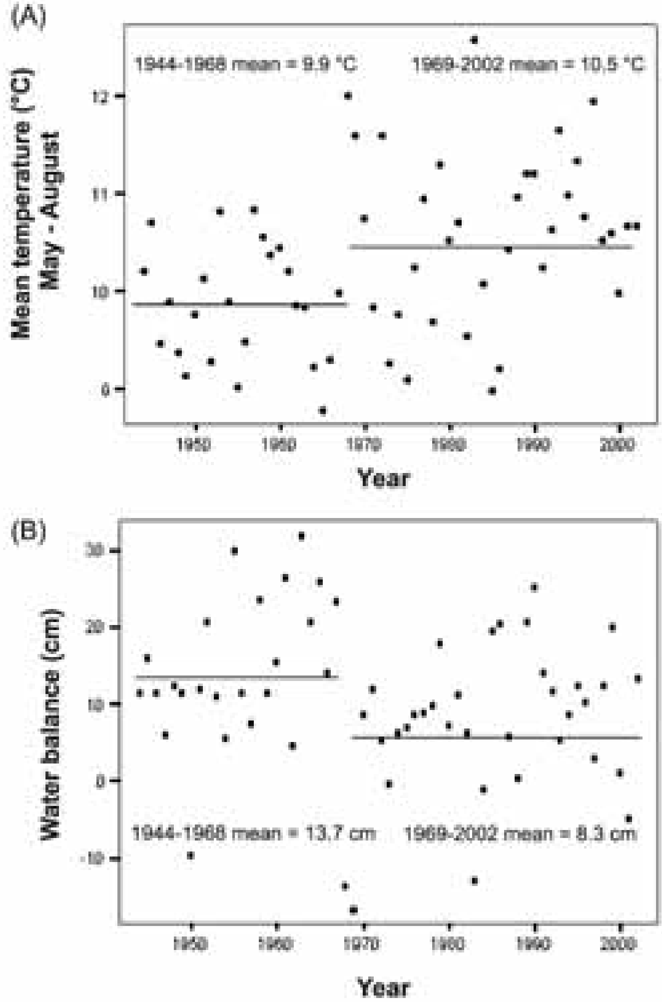
Aerial photographs (from 1950 and 1996), field surveys, and dendrochronology were used to study ecological succession and drying across the landscape of Alaska's Kenai Peninsula at several spatial scales. Drying at the regional scale was studied using random point locations on aerial photos. On a subregional scale, an exhaustive water body census of three areas on aerial photos from 1956 and 1996 was performed. Field surveys representative of drying were analyzed and placed into drying classes. At nine field surveys, the height, transect position, and species of all woody stems were described along transects.

### Study site: the Kenai Peninsula

The Kenai Peninsula, located in south-central Alaska, is bordered on the west by Cook Inlet, the east by Prince William Sound, and the south by the Gulf of Alaska. It consists of two distinct physiographic provinces and is connected to the mainland by a 20-km segment between Turnagain Arm and Passage Canal (Fig. 1). The Kenai Mountains on the eastern side of the peninsula rise to 2000 m and cover 60% of the 41 644 km$^2$ peninsula. Glaciers and the 2072-km$^2$ Harding Ice Field dominate the southeastern section of the peninsula. The elevation of the Kenai Lowlands is generally less than 100 m. This region is dotted with many lakes, moraines, wetlands, and rivers. Sediments of the Tertiary Period underlie the lowlands. A valley glacier, which receded 10 000 years ago, filled much of Cook Inlet and covered most of the Kenai Lowlands (Rieger et al. 1962), leaving a mantle of loess, which ranges in thickness from a few centimetres to several metres. Also, the Kenai Peninsula is in a no-permafrost zone of Alaska (Miller and Whitehead 1999).

The Kenai Peninsula is influenced by both maritime and continental climate patterns. Prince William Sound induces a

**Fig. 2.** (A) City of Kenai mean May to August temperatures, 1944–2002. (B) City of Kenai water balance 1944–2002. Water balance = precipitation – potential evapotranspiration.




rainy, warm maritime climate on the eastern coast, while the western side has a colder, drier continental climate. The east coast collects an average of 250 cm/year, while the study area, western and central peninsula, average only 46 cm/year. Because of the coastal influence, temperatures are more moderate than in interior Alaska. Climate data for the Kenai Lowlands reveal both an increase in temperature (0.6 °C) and a decrease in water balance (5.4 cm) over the past 50 years (Fig. 2) (National Climate Data Center 2003).

Forest vegetation on the Kenai Lowlands is typical of interior boreal forests and is dominated by a mixture of black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), quaking aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.). The dominant tree species of the Kenai Lowlands is black spruce, which is found on well-drained and poorly drained soils.

The Kenai National Moose Range was established by Franklin D. Roosevelt in 1941 to preserve moose habitat and in 1980 became the nearly 13 000 $km^2$ Kenai National Wildlife Refuge (KNWR). About two-thirds of KNWR is in the Lowlands. Kettle ponds, muskegs, and closed and open lakes on the Kenai Lowlands portion of the KNWR were studied for indications of drying and succession. Kenai Lowlands drying was studied on three spatial scales: regional, subregional, and local field sites.

## Regional analysis: overall drying trend

Regional analysis used a GIS to select 1113 random point locations on orthorectified aerial photos of the Kenai Lowlands taken in 1950 and 1996. The black and white 1950 and 1996 aerial photos had spatial resolutions of 3 and 1 m respectively and covered a total study area of 2210 $km^2$. Both sets of photos were taken between June and August of their respective years. Climate data reveal that 1950 was one of the driest years in the last half century, while 1996 was not abnormal (Fig. 2). Also, the mean May through August temperature in 1950 was over 1 °C cooler than in 1996 (Fig. 2). Using the aerial photos, each random point was classified visually into one of four coarse wetland categories for both 1950 and 1996: "water", "wet", "open", or "wooded". "Water" was a lake or large pond and showed itself on aerial photos as a smooth, black, self-contained area with smooth edges. "Wet" was a wetland and showed itself on aerial photos as patchy, small, dark black areas dotted on the landscape. "Open" was a lack of forest cover without water, or wetness, and showed itself on aerial photos as smooth light gray to white areas. It is possible that some areas of both "wet" and "open" supported some small woody shrubs that were not perceptible on aerial photos. "Wooded" was forest cover, which showed itself on the aerial photos as a mosaic of small, rough gray, white, and black dots that were interpreted as shrubs and (or) trees.

The Kenai Lowlands have a history of extensive burns, with the most recent and major documented fires in 1915, 1926, 1947, 1969, and 1974. These burn areas covered about 1550 $km^2$, almost 70% of the study area. Since wildfire initiates succession (Clark et al. 2003), stratification determined whether successional changes occurring over the 50 years of study were due primarily to climate change or were a response to burn history. We separated the random point locations in the burn areas, referred to as "burned", from random point locations outside the burn areas, referred to as "unburned". Burned areas were combined regardless of age, but excluding the relatively small 1974 burn (approx. 15 $km^2$), as no random point locations fell in its area. In total 567 and 546 points were located in burns and unburned areas, respectively.

A Markov transition matrix is a model of stochastic processes in which a variable has probabilities of staying in a current state or moving on to another state within a single time step. In this study, the possible states were "water", "wet", "open", and "wooded", while the time step was 50 years. In matrix m, element $m_{ij}$ gives the probability of going from row state *i* to column state *j*. Rows give coarse wetland states in 1950 and columns give coarse wetland states in 1996. An absorbing state in a Markov transition matrix is one that, once entered, cannot be exited, and so the probability of staying within an absorbing state is one ($m_{ii}$ = 1) and all other transitions for that row are zero ($m_{ij}$ = 0) (Jones and Smith 2001).

Markov models rely on several assumptions: (1) spatial distribution is not influential (Wooton 2001); (2) transition probabilities are stationary and do not change with time (Hobbs 1983); and (3) transition to another state is dependent only on the previous state, a condition known as the Markov property (Deo 1974). The first assumption of spatial influence is violated, as succession may occur differently near the foot of the Kenai Mountains compared with the shores of Cook Inlet (Fig. 1). Assumption 2 is also violated, specifically with regard to ecological succession. This is evident on the Kenai Peninsula as a result of anthropogenic events such as construction of roads and oil development as well as natural events like earthquakes. Finally, the Markov model often wrongfully disregards the influence of history as a precipitator of change (Tanner et al. 1996). Even though there are clear limitations with Markov modeling, ecological succession has been modeled successfully using Markov transition matrices in both river and forest communities (Horn 1975; Lippe 1985; Hobbs 1983; Hobbs and Legg 1983; Wooton 2001).

The observed transitions of all 1113 random point locations from 1950 to 1996 were used to construct a Markov transition matrix, m. In spite of its clear violations of assumptions, which preclude precise modeling, the Markov transition matrix, with elements estimated from changes seen between 1950 and 1996, helps to show how the drying trend could unfold if it continued into the future. The distributions were calculated by multiplying the current distribution of states by $m^n$, where $n$ is the number of 50-year time steps.

### Within-region drying trends for standing water bodies

To study within-region trends, the Kenai Lowlands region was divided into three 342-km$^2$ subregions (Fig. 1): Mystery Creek, Swanson River, and Tustumena. Each of these subregions was half of a digitally orthorectified quad. These subregions were chosen because they each represent different geographic areas of the Kenai Lowlands: Mystery Creek was the easternmost of the three and closest to the Kenai Mountains; Swanson River was in the north-central area of the Kenai Peninsula and nearest to Cook Inlet; and Tustumena was the southernmost of the three and closest to the western border of the KNWR boundary. Within each subregion, the 1950 photos were surveyed for all standing water such as lakes and ponds, but not rivers or streams. Each water feature's spatial extent in 1996 was compared to the extent in 1950, then characterized as having (1) increased in spatial area, (2) remained the same in spatial area, (3) decreased by less than 50% in area, or (4) decreased by more than 50% in area. We chose four classes for spatial extent because they allowed for simple and accurate visual interpretation of water bodies. Visual interpretation was used because many areas had an overlap in pixel value between water body edge and nearby forest, thus precluding automated computer analysis of spatial area.

### Local water body analysis: woody plant succession associated with drying

To further document the drying indicated by the regional and subregional results, 84 climate-sensitive (closed basin) sites (Fig. 1) were investigated in the field for their successional stage. Field sites covered a wide spectrum of conditions, including burned and unburned areas, spread across the three subregions of Swanson River, Tustumena, and Mystery Creek. Topographic maps, as well as 1950 and 1996 aerial photos, were used to select sites to represent drying and succession. Investigations qualitatively studied water level, vegetation, and aerial photos to place each site within a drying class. Drying classes were "unchanging", "more rapid falling", "slow falling", "long-term falling with recent fluctuation", and "long-term fluctuation". A water body in the class "unchanging" showed the same perceptible water level in both the 1950 and 1996 aerial photos and in the field in 2003, whereas a water body in the class "more rapid falling" showed greater than a 50% perceptible water level difference between 1950 and 2003 and supported young woody stems on former lake bed. The class "slow falling" showed less than a 50% perceptible water level difference between the 1950 aerial photos and field observations in 2003. This class also supported young woody stems on the former lake bed, but to a smaller spatial extent than "more rapid falling". A water body in the drying class "long-term falling with recent fluctuation" showed greater than a 50% perceptible water level difference between the 1950 and 1996 aerial photos, but the 2003 field visit revealed a water level perceptibly higher than that in 1996. This class was indicated by wholly or partially inundated young woody stems at the edge of the water body, as water level had been down long enough for growth, but had not been up long enough to cause woody stem death. Lastly, the drying class of "long-term fluctuation" showed less than a 50% perceptible water level change between 1950 and 1996, but the 2003 field visit revealed a water level greater than that in the 1996 aerial photos. Also, for 76 water bodies the depth of peat surrounding the water body, if present, was measured with a 4-m soil auger.

### Vegetation transects from field sites

Woody vegetation was described for nine water bodies that were partially dried in the 1996 photo and identified on 1950 maps and aerial photos as closed basin. Belt transects, at sites that showed clearly quantifiable successional trends, were 5 m wide and covered various lengths, as needed to capture vegetative trends. Some transects ran across the whole former water body, when water levels allowed, and others stretched from the water's edge to the mature forest edge. Throughout the transect area, the height, taxonomic classification, and transect position of each woody stem was recorded. Also, at two of these transect sites, the ages of woody stems on the apron (the area between water's edge and mature forest edge) were determined through dendrochronology.

## Results

### Regional analysis: overall drying trends

In 1950, the sample points were classified as follows: wooded (57%), open (31%), wet (5%), and water (7%). Therefore, approximately 12% of the region could be inferred as having some level of wetness. The results in 1996 showed that the proportion of cover classes were as follows: wooded (73%), open (20%), wet (<1%), and water (6%), indicating some degree of drying. For the sample data, there was a 28% increase in the wooded class and decreases of 34% for open, 88% for wet, and 14% for water.

To determine whether half-century changes in coarse wetland classifications (wooded, open, wet, and water) were due primarily to climate change or were in response to burn history, sample data were partitioned into two groups based on fire

**Table 1.** Distribution of wetland states for 1950 and 1996 burned and unburned sample locations.

| Sample location | % water | % wet | % open | % wooded |
|---|---|---|---|---|
| Burned areas: 1950 | 7 | 6 | 32 | 54 |
| Unburned areas: 1950 | 7 | 4 | 30 | 60 |
| Burned areas: 1996 | 7 | <1 | 22 | 70 |
| Unburned areas: 1996 | 5 | <1 | 19 | 76 |

occurrence in the 20th century (i.e., "burned" versus "unburned"). These burn areas together cover about 1550 $km^2$ (Andy DeVolder-Thesis 2002). The burned areas of all years were combined and analyzed as a single area sampled by 567 total random points (51% of the total). This sample showed that in 1950, the burned areas differed little from the 546 points in unburned areas (Student's $t$ test, $t = 0.992$, $p < 0.05$). Similarly, comparison of burned and unburned points across the 1996 landscape also suggested little difference (Student's $t$ test, $t = 0.992$, $p < 0.05$) (Table 1).

The changes that took place between 1950 and 1996 were quite similar in burned and unburned areas (Table 2). The major difference was that the number of burn points classified as "water" decreased 7%, while the number of unburned points decreased by 22%; all other percent changes differed by less than 5% between burned and unburned sample points. It appears that landscape change did not depend substantially on burn history.

Using all sample data, a Markov transition matrix, **m**, was constructed, given by

$$\mathbf{m} = \begin{array}{c} \\ w \\ o \\ wt \\ wtr \end{array} \begin{array}{c} \begin{array}{cccc} w & o & wt & wtr \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0.503 & 0.496 & 0 & 0 \\ 0.069 & 0.879 & 0.052 & 0 \\ 0.038 & 0.051 & 0.051 & 0.859 \end{pmatrix} \end{array}$$

This matrix reveals transitions between 1950 and 1996 wetland states. Matrix element $\mathbf{m}_{ij}$ gives the probability of going from row state $i$ to column state $j$. Row headings give coarse wetland state in 1950 and column headings give coarse wetland state in 1996 (w, wooded state; o, open state; wt, wet state; wtr, water state). The upper off-diagonal elements are all zero, suggesting that there is no apparent wetting taking place (Fig. 3). The coarse wetland state of "water" remained "water" for 86% of all the random points. Points classified as "wet" remained wet from 1950 to 1996 for only 5% of random points. "Open" remained "open" between 1950 and 1996 for roughly half the points and transitioned to "wooded" for the other half. Lastly, the state of "wooded" proved to be an absorbing state; all random points classified as "wooded" in 1950 were also "wooded" in 1996.

The Markov matrix, m, estimated from the changes seen between 1950 and 1996, was used as a highly speculative, but suggestive exercise to examine the potential vulnerability of wetlands if the current transition probabilities remain stable for the next 50 years. The Markov treatment indicates the drying trend established from 1950 to 1996 will continue to 2050, with decreases in all states except "wooded" (Table 3).

**Table 2.** Percent change between 1950 and 1996 wetland states for burned and unburned areas.

| Sample location | % water | % wet | % open | % wooded |
|---|---|---|---|---|
| Burned ($n$ = 567) | −7 | −88 | −31 | +30 |
| Unburned ($n$ = 46) | −22 | −87 | −37 | +27 |

### Within-region drying trends for standing water bodies

The results of the exhaustive localized water body survey showed that more than 60% of the water bodies experienced some level of drying, but the level of drying varied by subregion (Fig. 4). The Swanson River subregion had the most water bodies unchanged in size between 1950 and 1996 (49.2%). Conversely, the subregions whose water bodies showed the most shrinkage in size from 1950 to 1996 were Mystery Creek (74.6%) and Tustumena (73%). In the 1996 aerial photos each subregion had more than one-third of its water features with a spatial extent half or less than their 1950 spatial extent. Overall, for the 820 total water bodies surveyed in the three subregions, roughly one-third (34.8%) showed no change in spatial extent from 1950 to 1996, less than a one-third (27.8%) lost less than half their area, and more than a one-third (37.4%) lost greater than half their area. Significantly, none of the three subregions surveyed had water features that increased in spatial extent from 1950 to 1996 (Fig. 4).

### Local water body analysis: woody plant succession associated with drying

To further document the scope of the drying indicated by the regional and subregional results, 84 climate-sensitive sites (Fig. 1) were investigated in the field for their successional stage. The sites analyzed in the field covered a wide spectrum of conditions, including those in and out of burned areas and across the three subregions of Swanson River, Tustumena, and Mystery Creek. These investigations qualitatively studied water level, vegetation, and aerial photo comparisons to place each site within a drying class. Over 80% of the 84 field sites showed some level of drying, with nearly half experiencing "slow falling" and less than 20% "no change" (Fig. 4). Of the 84 sites, 76 had peat depths measured for each of the water bodies. Fifteen of the 17 sites classified as "rapid falling" had peat depths less than 2 m or no peat. Eleven of the 15 sites classified as "unchanging" had peat depths greater than 2 m (Fig. 5). In other words, peat depth seemed to be negatively associated with drying.

### Vegetation transects from field sites

At nine sites, transects were used to describe the woody vegetation in water bodies described as "closed basin" on 1950 maps, but partially dried in 1996. In most cases, woody vegetation indicated moisture status of the now-dry lake beds. Lake beds with woody vegetation, especially lake beds with upland vegetation, maintained lower moisture levels than lake beds lacking woody vegetation. Generally, mean height of woody vegetation on the former lake bed was >100 cm for the first 5 m from the forest edge and 25–50 cm high from 5 to 20 m from the forest edge (Fig. 6). In every case, the mean height of woody stems was not zero along the full length of the transect, suggesting that transect area has been

**Fig. 3.** Transitions between wetland states based on random point classification of states' changes in 1950 and 1996 aerial photos.

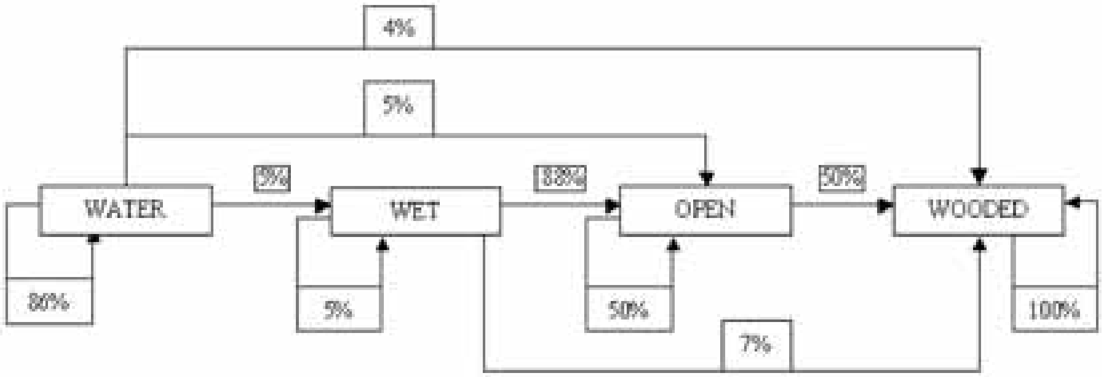



**Table 3.** Initial and future distributions of coarse wetland states using Markov matrix, **m**.

| Distributions | Year | % water | % wet | % open | % wooded |
|---|---|---|---|---|---|
| Observed | 1950 | 7.0 | 5.0 | 31.0 | 57.0 |
| | 2000 | 6.0 | 0.6 | 20.0 | 73.0 |
| Predicted | 2050 | 5.2 | 0.3 | 11.0 | 84.0 |

**Fig. 4.** Spatial changes of water bodies from 1950 to 1996 in three subregions.

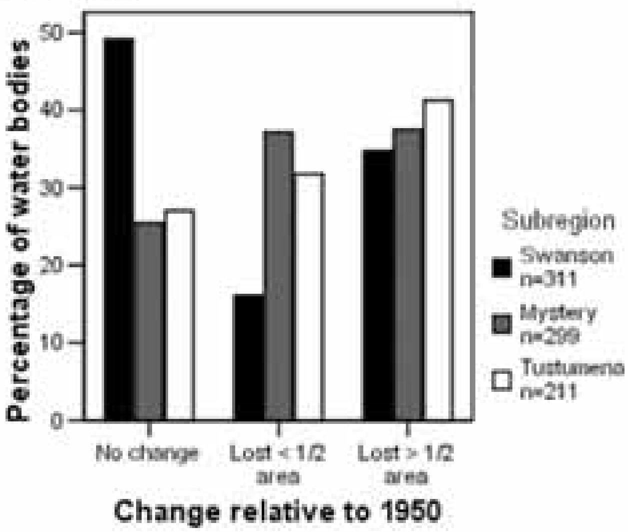
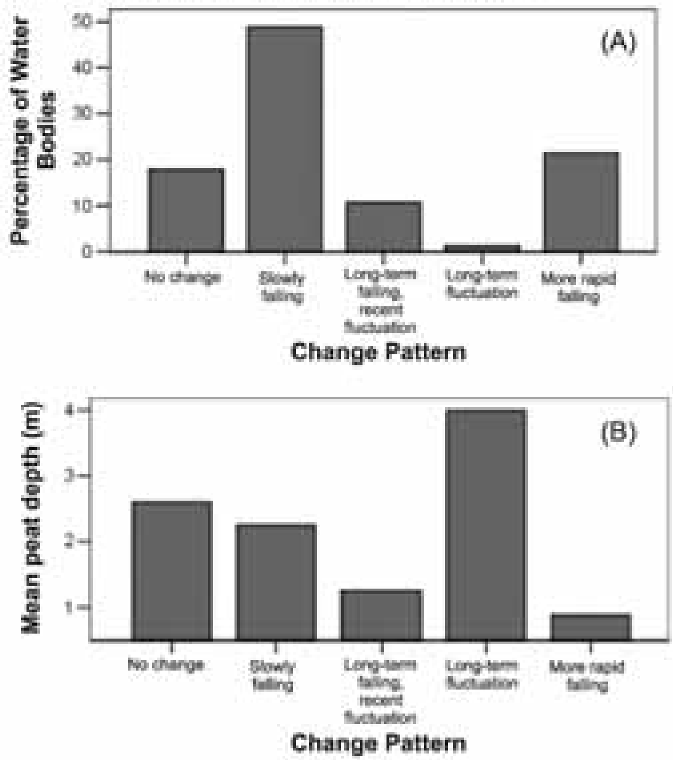
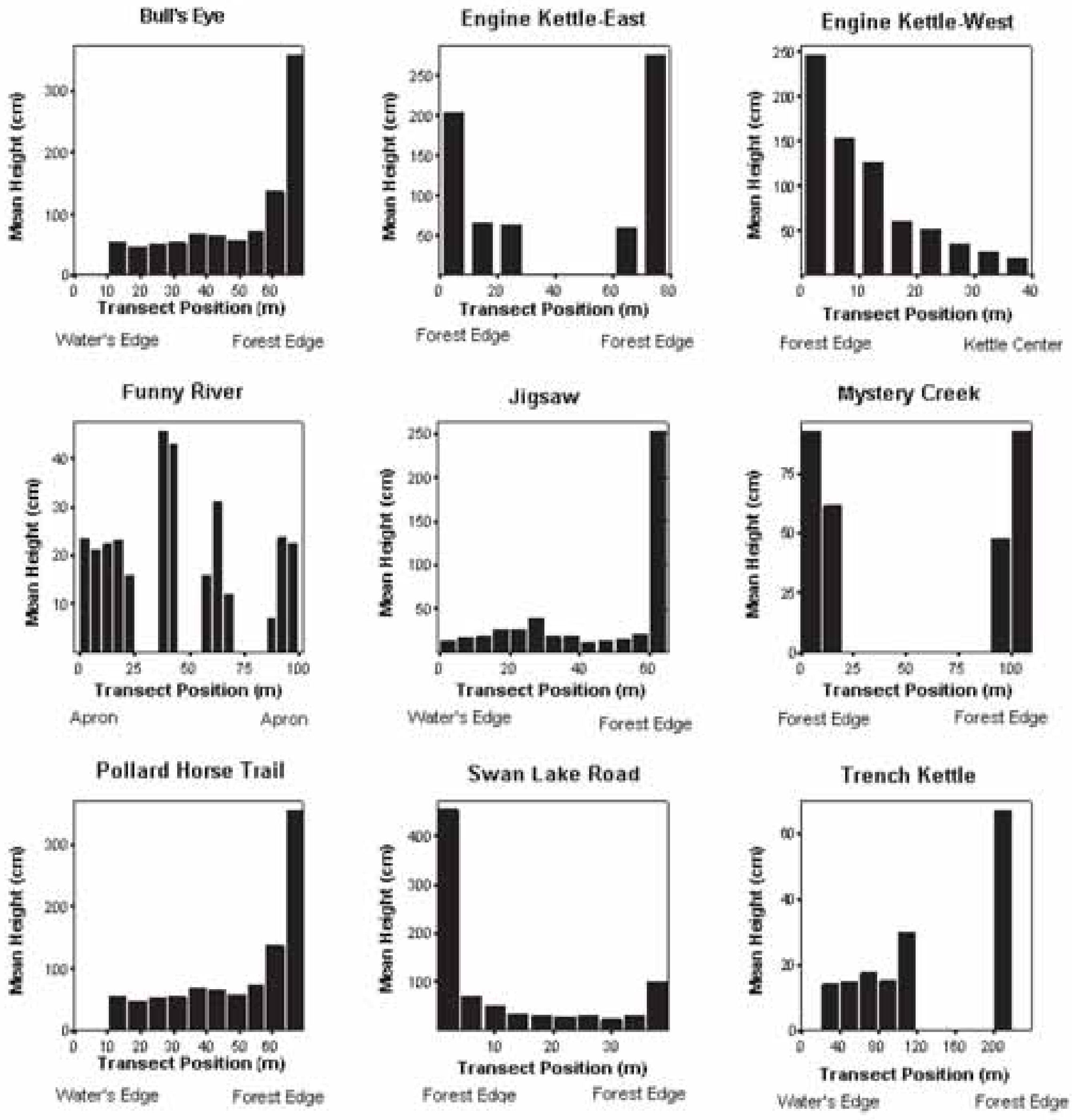



**Fig. 5.** (A) Change patterns of sites studied in local water body analysis ($n$ = 84). (B) Patterns of change in field visited water bodies with relation to surrounding amounts of peat.




dry long enough for woody vegetation to become established. Some transects (Pollard Horse Trail, Bull's Eye, Trench Kettle, Jigsaw) showed signs of self-thinning, with a decrease in the density of stems (Fig. 7) as their corresponding mean heights (Fig. 6) increased. The distribution of height is of particular interest because taller stems under stable growing conditions can be assumed to be older than shorter stems, thereby age typing the drying phenomenon. Consistent with this idea, the field transect at Pollard Horse Trail indicated a positive correlation between transect position (distance from water's or forest's edge) and stem age ($r^2$ = 0.78) (Fig. 8). The oldest woody stems, excluding those in mature forest, on the Pollard Horse Trail transect were 25 years old, suggesting the start of water body drawdown began around the mid-1970s. The field site at Mystery Creek also showed a positive correlation between stem transect position and stem age ($r^2$ = 0.93) (Fig. 8). The oldest woody stem at the Mystery Creek field site was 15 years old, suggesting a more recent water level drop during the late 1980s to early 1990s. The degree of drying on the nine former lake beds was also evident from the relative proportion of all woody vegetation that could be classified as facultative upland according to the US Fish and Wildlife Service classification system (Reed 1988). Essentially, all the transects indicated an overall shift from a wetland to an upland habitat, despite variability among former water bodies in the relative proportion of facultative woody plants, varying from 100% facultative upland at Pollard Horse Trail Site to about 50% facultative upland at others (Bull's Eye, Engine Kettle-East). While about half of the field transects (Mystery Creek, Trench Kettle, Engine Kettle-East, Pollard Horse Trail) showed a uniform pattern of inward encroachment, others showed some woody plant recruitment expanding out from the center (Funny River, Swan

**Fig. 6.** Stem heights are mean heights of woody stems, as function of transect position, for nine sites. Different scales used to reveal the absolute trends at each site, which would be unclear if all graphs used the same scales.



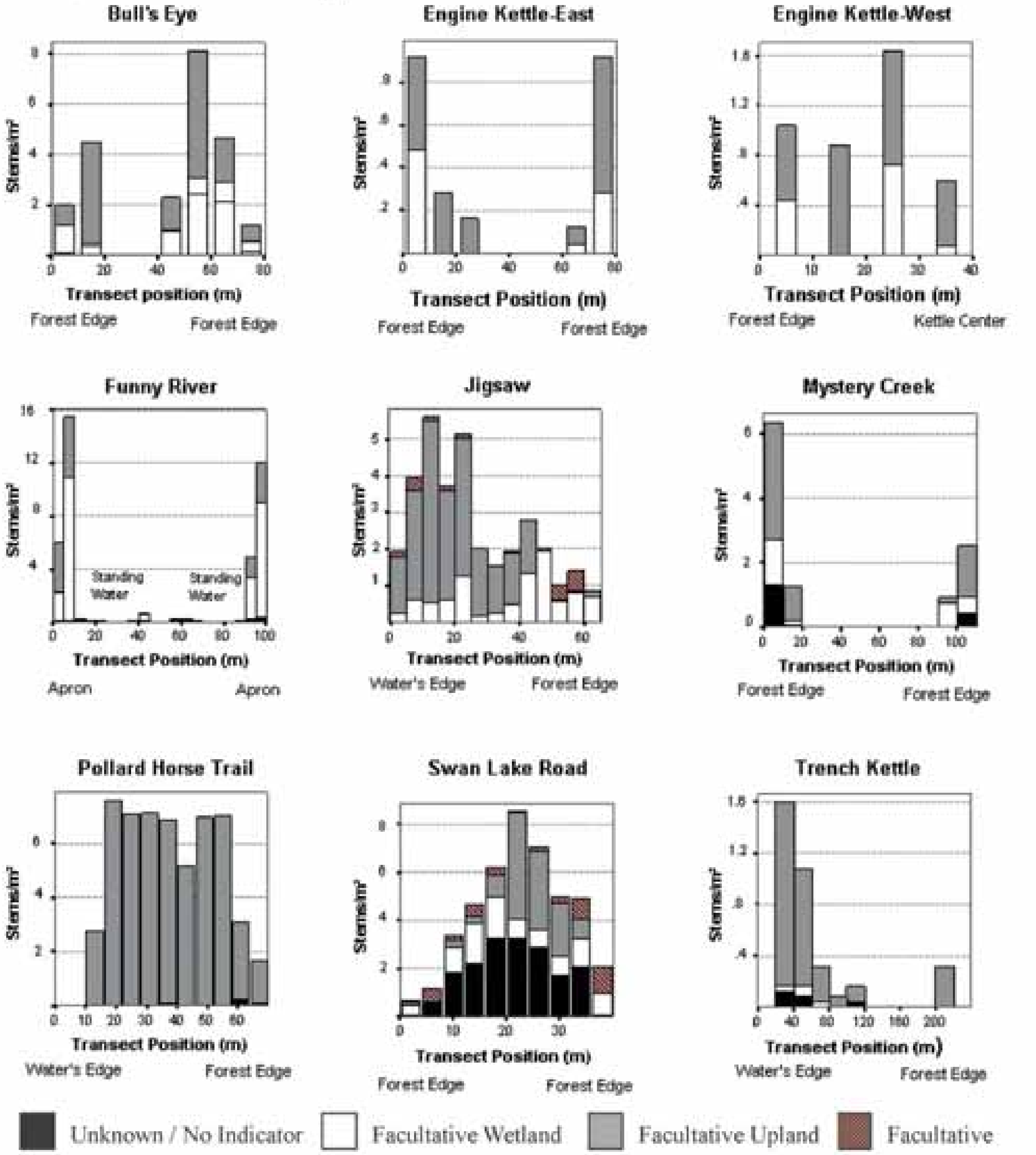

Lake Road), patterns most likely reflecting the bathymetry of individual water bodies.

## Discussion

The results of this study document that the Kenai Peninsula is becoming both woodier in vegetation and drier. Our regional analysis of random points between 1950 and 1996 indicate increased forest cover and decreased open and wet areas in both burned and unburned areas. Our census of water bodies in three subregions indicate that almost two-thirds of water bodies investigated showed some level of decrease in spatial area. Over 80% of field sites visited experienced some level of drying. Our field transects also indicate substantial invasion into former lake beds by facultative upland plants. Dating of woody stems on three drying wetland areas placed recruitment of most stems within the last 100 years, with sharp declines in recent seedling recruitment.

Our results corroborate other studies that relate wetland drying to climate change. In northern latitudes, climate change

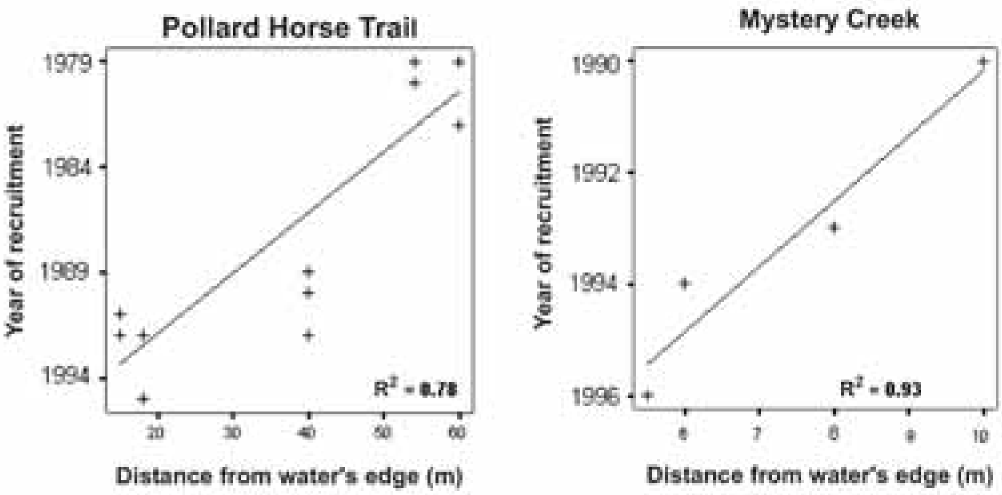
**Fig. 7.** Woody stem density, classified by wetland indicator category, along nine field transects. Different scales used to reveal the absolute trends, which would be unclear if all graphs used the same scales.




is expected to precipitate vegetation shifts including changes in wetland ecosystems (Arctic Climate Impact Assessment 2004). Drying of lower latitude wetlands as a result of increasing air temperatures has already been documented (Kusler 1999). Consistent with Kusler's claim is the prediction by Sorenson et al. (1998) that the number of closed basin vernal ponds in central North America could decrease from 1.3 million ponds to less than 0.8 million by the year 2060. Temperature appears most important to drying, as areas with increased temperatures show signs of substantial drying even when precipitation has remained constant (Kusler 1999).

In the Kenai Lowlands both increased temperatures and decreased precipitation over the last 50 years seem to be driving forces in wetland drying. Climate records from the Kenai Peninsula city of Kenai (National Climate Data Center 2003) show that the mean May–August temperature was

**Fig. 8.** Relationship between stem transect position and year of recruitment.




9.9 °C during 1944–1968 and 10.5 °C during 1969–2002 (Fig. 2). Moreover, in 1950 the mean May–August temperature was 9.7 °C, compared with 10.8 °C in 1996. More dramatically, Kenai precipitation records show nearly a 40% decrease in the mean annual water balance (precipitation – potential evapotranspiration), dropping from a mean of 13.7 cm between 1944 and 1968 to a mean of 8.3 cm between 1969 and 2002 (Fig. 2). Climate data indicate that our aerial photo analysis results are not just a function of comparing the difference between two unrepresentative years. Moreover, it actually might be underestimating the extent of the drying since the base-line year, 1950, was a dry year and 1996, the comparison year, was a normal moisture year (Fig 8). Supporting evidence of regional changes comes from aerial photos and transition matrices used to show that, from 1950 to 1997, 37% wetlands in an urbanized watershed of Anchorage, Alaska, became uplands through drying and (or) succession (Abbey Wyers-Thesis 2001). Located approximately 100 km north of the Kenai Lowlands and in the same ecoregion (Nowacki et al. 2001), Anchorage has very similar climate patterns. For example, over the past 50 years Anchorage and the city of Kenai have had, respectively, average annual high temperatures of 6.1 and 5.6 °C and average annual precipitation of 40 and 48 cm (National Oceanic and Atmospheric Administration 2004).

On a continental scale, boreal forests have already experienced declining water levels in wetlands (Kusler 1999) and decreased soil moisture (Weller and Lange 1999). Relatively small changes in water balance can alter surface soil or ground water sufficiently to reduce wetland size or initiate conversion of wetlands to uplands (Laine and Vanha-Majamaa 1992; Vasander et al. 1993; Jukaine and Laiho 1995). In boreal regions, Jukaine and Laiho (1995) substituted the influence of climate change induced peatland drawdown with artificial peatland drainage of varying years (3–55 years since drainage). This experimental drawdown allowed for the study of long-term vegetation changes associated with climate-induced drying. An increase in tree growth followed drainage, initiating succession from wetland species (i.e., *Carex lasiocarpa* and *Ledum palustre*) to forest species (i.e., *Rubus idaeus* and *Vaccinium vitis-idaea*). The successional gradient of vegetation that followed experimental water level decrease provides strong evidence that the proportion of upland vegetation generally increases with time since drainage (Jukaine and Laiho 1995). These experimental results are consistent with our observations in dry lake beds on the Kenai Peninsula, where upland species are proliferating. Essentially, our results are in accordance with the notion that climatic shifts influence, and will continue to influence, high-latitude environments by initiating shifts in both composition and distribution of vegetation types (Ager 1997). Our results are consistent with those of other recent studies indicating that vegetation and water body changes are occurring in northern regions of Alaska (Sturm et al. 2001; Silapaswan et al. 2001; Stow et al. 2004; Arctic Climate Impact Assessment 2004).

In this study, we demonstrated that there have been substantial increases in woody areas at the expense of open areas on the Kenai Lowlands, as well as more substantial loss of wet areas than open water areas. These results are expected given typical successional patterns. The time scale of our investigations also suggests that even with intervening fires, the woody vegetation recovered sufficiently quickly to obscure fire changes. It is most likely that a wooded state is not an absorbing state because of eventual and likely fire exposure. If a transition to a nonwoody state did occur, it would likely be a temporary shift to open, before returning to wooded as a result of postfire succession. Because of postfire succession and the time period between photo analysis and most recent major burn (29 years), wooded is an absorbing state in our study. If photos were analyzed more frequently after burns, then wooded would likely not be absorbing for each transition.

The results of the exhaustive water body census (roughly twice as many water bodies showed signs of drying as those that showed no change) are expected given the changes in precipitation, temperature, and transitions among coarse wetland states, but the census likely underestimates overall drying trends. Indeed our analyses may underrepresent the actual drying that has already occurred. Firstly, some former water bodies were already dried pans in the 1950 photos and were thus omitted from the water body survey. Secondly, some water bodies may have changed from 1950 to 1996, but this change was undetectable based on aerial photo analysis. Some deep lakes could indeed be drying, but because of their size and (or) bathymetry they do not show perceptible change over this time period. Besides deep-water lakes, some other wetlands showed little change. In our local water body analysis, drying appeared to be negatively related to peat depth. This could be attributed to the substantial ability of *Sphagnum* peat to absorb and sequester water up to 20 times its own mass (Raven et al. 1992). This ability to retain moisture may explain why sites with greater than 2 m of peat dry more slowly than those with less than 2 m of peat: the drawdown is buffered by the extensive water-holding capacity of surrounding peat.

Responses to changing environmental conditions, predominantly water depth, can result in unique vegetative zones with abrupt boundaries that reflect community composition (Cronk and Fennessy 2001; Mitsh and Gosselink 1993). Here, analysis of transects indicate a drying pattern reflected in three vegetative zones. The forest zone began with mature black spruce at the forest edge. Community structure changed as the forest zone met the apron, an area between the water and mature forest. The apron zone often supported an initial cover of *Calamagrostis* grass, classified as facultative or facultative wetland depending on species (Reed 1988). The apron zone supported young woody recruitment of black spruce (*Picea mariana*) and white spruce (*Picea glauca*), paper birch (*B. papyrifera*), and quaking aspen (*Populus tremuloides*). Below the apron zone was a third more mesic community. This wetland zone consisted of wetland plants including species of *Carex* spp., *Chamaedaphne calyculata*, and *Menyanthes trifoliate*. The vegetation transects documented only woody species' heights, but these zonal classifications are suggestive of the role played by other indicator species like *Calamagrostis*. This general pattern of three zones (i.e., forest, apron, and wetland) was quite consistent across all nine sites. Two of our vegetation transects (Jigsaw and Pollard Horse Trail) showed an inverse relationship between transect position and stems per square metre. During succession, self-thinning will reduce the number of stems while height and biomass of survivors increases (Adler 1996). A decrease in stems per square metre and an increase in height may continue until height and density of woody stems resemble mature forests.

Our multiple-scale analysis documents extensive changes across the landscape of the Kenai Peninsula Lowlands since 1950. These changes include (1) a substantial increase in woody cover over the last half century; (2) measurable water body shrinkage and wetland drying; (3) invasion of lake beds by woody and facultative upland species. Apparently, nonchanging water bodies may indeed be drying, but not detectably so, given our techniques and low surface area to water volume ratio, surrounding peat sponge, or location in an open basin, where inflow keeps them at a somewhat stable volume and area. Given a 1–2 °C temperature rise and a 40% decrease in mean annual water balance on the Kenai Lowlands over the last half century, it appears likely that climate change is driving wetland drying and vegetative shifts to predominantly woodland and forest.

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