Perennial Pepperweed Infestation on the Cosumnes River Experimental Floodplain

A Report to the California Bay-Delta Authority

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Abstract

Riparian floodplains present a unique challenge for restoration management, in that these are, by definition, dynamic, constantly changing ecosystems. As restoration projects are initiated and progress through time, both native and invasive species can become established. During the initial invasion and stages of establishment and colonization, management may be effective in controlling the impact of non-native invasive species in restoration areas. However, it is critical to have effective information on the location and nature of weed populations to prioritize and sustain management activities. We use a combination of field monitoring and spatial modeling to determine rates of *Lepidium latifolium* spread on a riparian floodplain restoration site and to determine what, if any, environmental and physical factors may limit expansion of *Lepidium* infestations at this site. Our research combines tracking of population dynamics with spatial analyses to assess differences in *Lepidium* invasion as a function of distance to potential propagule source, degree of shading, and degree of inundation resulting from microtopographic floodplain gradients.

Introduction

The process of ecosystem restoration typically involves active manipulation of existing environmental conditions in order to create desired changes in ecosystem properties. Although the intent of vegetation restoration is the assemblage of plant species to form a desired community composition, the invasion of non-native species into the assembly can result in the subsequent domination of the community through exclusion and competition. The management and control of invasive species has thus become a dominant component of most ecosystem restoration efforts.

Riparian floodplains present a unique challenge for restoration management, in that these are, by definition, dynamic, constantly changing ecosystems. Riparian floodplains are subject to flood pulse events (Junk, Bayley et al. 1989; Tockner, Malard et al. 2000), which depending on their size, frequency, and timing, can drastically alter the environment through the influx of nutrients (Ahearn, Viers et al. 2006), scour and deposition of fluvial substrates (Florsheim and Mount 2002; Florsheim and Mount 2003), the flushing and deposition of organic matter (Ahearn, Viers et al. 2006), and the exchange and movement of floodplain organisms (Grosholz and Gallo 2006).

The impact of floodplain processes on organisms can be drastic. Floodplains can create environments ideal for the rearing of native fishes, or can serve as nursery and feeding grounds for invasive fishes, thereby exacerbating pressures on native fish populations (Moyle, Crain et al. 2003; Ribeiro, Crain et al. 2004). Similarly, floodwaters can transport propagules of desirable native plant species from upstream, depositing seeds, branchlets and root fragments to establish on recent deposits of fertile alluvium. Native species spread in this way include trees such as cottonwood (*Populus fremontii*), willow (*Salix* sp.), box elder (*Acer negundo*), Oregon ash

(*Fraxinus latifolium*) and Valley oak (*Quercus lobata*), and shrubby or herbaceous plants such as California rose (*Rosa californica*), umbrella sedge (*Cyperus eragrostis*), cocklebur (*Xanthium strumarium*), and others. Propagules of non-native plants are also transported onto a floodplain during high water. Non-native plant species establishing this way at the Cosumnes River Preserve include black locust (*Robinia pseudoacacia*) in the overstory, and a multitude of understory species including wild radish (*Raphanus sativa*), poison hemlock (*Conium maculatum*), wild carrot (*Daucus carota*), and perennial pepperweed (*Lepidium latifolium*).

Perennial pepperweed (hereafter referred to as *Lepidium*) has been identified as a significant threat to restoration of riparian areas throughout California's San Francisco Bay-Delta region, as it is a highly invasive perennial herb that can thrive in a wide range of habitats including riparian areas, wetlands, marshes, and floodplains (Young, Turner et al. 1995; Bossard, Randall et al. 2000). *Lepidium* has already invaded many habitats throughout the San Francisco Bay-Delta area (Trumbo 1994; Grossinger, Alexander et al. 1998), and is of particular concern in areas where active restoration is underway. Once established, this plant creates large monospecific stands that displace native plants and animals, and can alter soil composition by concentrating salts at the surface (Young, Turner et al. 1995; Blank and Young 1997; Young, Palmquist et al. 1997; Renz and DiTomaso 1998). It interferes with regeneration of cottonwood and willow species, as well as key herbaceous species, in riparian and wetland areas (Young, Turner et al. 1995).

Background

Lepidium is a perennial herb in the Brassicaceae (mustard) family, and is known by the common names perennial pepperweed and tall whitetop. This herb of Euro-Asian origin was introduced into the U.S. in the 1930's and is now found throughout the western continental United States. Perennial pepperweed appears to be adapted to using soil water with high salt content, but is not an obligate halophyte. It grows in freshwater, brackish to saline, and alkaline environments in a wide range of habitats including riparian areas, wetlands, marshes, meadows and floodplains (Young, Turner et al. 1995; Bossard, Randall et al. 2000; Howald 2000; Renz and Blank 2004). The US Bureau of Land Management and 10 western states classify *L. latifolium* as a noxious weed (Chen et al. 2005). It is on the California Invasive Plant Council (CalIPC) A-list of exotic pest plants and on the California Department of Food and Agriculture's B list of noxious weeds, due to its highly invasive and ubiquitous nature.

The biology and ecology of *Lepidium* enables highly effective propagation and establishment in riparian areas. The plant spreads both vegetatively and through seed set. Established plants produce high numbers of seeds - up to 16 billion seeds per hectare in stands at the density of 200 tillers m^{-2} in a northern California valley (Blank and Young 1997; Young, Palmquist et al. 1997). Seeds subjected to fluctuating temperatures, typical of soil surfaces, have germination rates of 80 to 94% (Miller, Young et al. 1986). At constant cool to warm temperatures typical of deeper soils, germination rates are lower (26-43%) but still biologically significant (Miller, Young et al. 1986). Spread by perennial root fragments is considered the most common method of dispersal in riparian areas (Renz 2000). *Lepidium* roots allow bank erosion due to their low density in the soil, easily fragment, float, tolerate dry conditions and resist desiccation (Renz 2000). Although the ability of *Lepidium* to successfully invade and develop monocultures in riparian areas is clear, there is little information on spatial and temporal patterns of invasion and spread. In a list of research needs, Renz (2000) noted that environmental, physical, and spatial factors limiting expansion of *Lepidium* infestations need to be identified.

Study Narrative

The Cosumnes River Preserve encompasses approximately 18,000 hectares along a 16 km reach of the Cosumnes River. Preserve lands are primarily located in the lower floodplain of the river on the eastern border of the San Francisco Bay Delta. Within the Preserve, our study area is a 1.26 km^2 (312 acre) restored floodplain in Sacramento County along the lower Cosumnes

River. Soil within the site is all Cosumnes silt loam soil, and was formerly farmed for rice and tomatoes. The site is surrounded on three sides by a levee system. When an accidental levee breach occurred in 1985, a sand splay complex formed downstream from the levee failure. The area was not cleared, and a riparian cottonwood-willow forest grew on the sand splay. The success of this passive restoration prompted experimental engineering of 30m breaches in 1996 along the several levees surrounding the former fields (Figure 1).

Lepidium is considered a high-ranking threat to critical habitats within the Cosumnes River Preserve (CRP 2002). Numerous infestations of *Lepidium* occur in agricultural, riparian and roadside areas upstream and in proximity to the Cosumnes River Preserve. Potential sources of root fragments and seeds on the Preserve include waterways, nearly annual floodwaters, vehicle and foot traffic. *Lepidium* is a priority for control by Preserve managers because of its highly invasive nature, the threat it poses to native habitats including valley oak riparian forest, mixed riparian forest, seasonal and permanent wetlands and associated uplands.

To combat the threat of Lepidium, information is needed on population locations, propagule pressure, population trajectories, and best methods of control. Little is known about the factors promoting and/or limiting the expansion of perennial pepperweed, especially in floodplain settings (Renz 2000). Population trajectories have not been established for floodplain systems experiencing initial phases of invasion. Prior to the initiation of semi-passive floodplain restoration activities on the Preserve, only limited monitoring of *Lepidium* infestation and spread was conducted. Our aim was to determine the relative relationship of physical and environmental site characteristics to initial establishment and subsequent trend of Lepidium populations on the Cosumnes River Experimental Floodplain. We use a combination of field monitoring and spatial modeling to help gauge the impact of *Lepidium* infestation on semi-passive restoration efforts and determine what, if any, environmental and physical factors may limit expansion of *Lepidium* infestations.

Our research combines tracking of population dynamics with spatial analyses to assess differences in Lepidium invasion success by distance to potential propagule source, degree of shading, and degree of inundation resulting from microtopographic floodplain gradients.

Field Methods

Field observations were recorded from 2002 to 2005 by conducting an inventory and monitoring Lepidium latifolium populations on the 312 acre restored floodplain. Complete surveys of all Lepidium patches on the floodplain were conducted during the summers of 2002, 2004 and 2005. Patches were defined as a minimum of one tiller and located at least 3 meters apart from another patch. For each patch we recorded number of tillers (individual, bolted shoots protruding from underground tillers and roots) and patch area, setting 1 m^2 as our minimum patch size. Patch size was estimated by length x width in 2002, and by either GPS polygon (if > 1 m^2) or visual estimate (if < 1 m^2 or if the area could not be circumscribed in the field). In 2004 and 2005 we also recorded a visual estimate of percent Lepidium latifolium cover within the entire patch.

GIS Methods

Patch Threshold Distance and Spatial Joining

Field-mapped patches were corrected to ensure merging of patches <3 meters apart as described in (Viers, Hogle et al. 2005)(Table 1). Overlay and identification of patches surviving from one year to the next was implemented using spatial join operations in a GIS.

Elevation

We used raster representations of floodplain elevation as digital elevation models (DEMs) to approximate elevation conditions and its derivatives, such as slope and aspect. One source of elevation data was the conversion of 30 cm contours developed for previous studies (see Florsheim and Mount 2002; Florsheim and Mount 2003; Florsheim, Mount et al. In Press). The other source of elevation data was from lidar – light detection and ranging or laser altimetry – acquired in July 2005 through a separately funded study from Watershed Sciences, LLC (Corvallis, OR). Watershed Sciences used an Optech 3100 sensor mounted inside a Cessna Caribou to collected ~8,000 ha at a 71 kHz pulse rate, resulting in 3.07×10^8 pulses returned. Horizontal accuracy was ± 0.5 m. Our independent verification of vertical accuracy using established benchmarks from Florsheim & Mount (2002) and positional measures from a real-time kinematic (RTK) precision survey instrument (1 cm±) concluded that base elevations were within 10cm (RMSE = 0.08 m; $R^2 = 0.997$; n = 16). LIDAR data were subsequently analyzed with 0.5 m horizontal resolution, and 1 dm vertical.

Euclidian Distance

We created raster data representations of distance from patches to landscape features including roads, rivers, sloughs, ponds, water features (including the above plus spring-flooded rice fields), levees, levee breaches, and 250-meter, downstream breach impact zones. All landscape features (e.g., roads, waterways, levees, breaches) were heads-up digitized over high-resolution, orthorectified aerial imagery flown in May 2002 and acquired from the California Department of Water Resources.

Canopy

Canopy delineations were created through heads-up digitizing of all recognizable trees (>1 m high) over aerial imagery at a scale of 1:3000. Identifiable trees in 2002 were delineated over true color imagery flown in May 2002 with a resolution of 30cm; tree canopies from 2005 were delineated over 30cm false-color imagery also obtained from Watershed Sciences LLC in July 2005, and supplemented by true color imagery at $1m^2$ resolution obtained by the State of California. We validated the 2005 canopy coverage data by using 78 independent 20m x 20m plots which were assessed for canopy closure using a handheld spherical densiometer, which showed a RMSE of 11.8% when compared to the digitized cover over the same macroplot.

Horizontal rate of canopy spread was calculated using an unmodified canopy percent, where CanopyPct = Canopy area within a patch/Total *Lepidium* patch area. Rate of canopy spread within a patch was calculated as

$r = (\ln (N_{t+x}/N_t))/x$

For example, rCanopyPct02to05 = ln((CanopyPct05 + 1))- ln(CanopyPct2002 + 1))/(2005-2002).

Data Analysis Methods

Rate of Increase

As *L. latifolium* populations are currently at low density within the study area (0.1% of the total acreage of the experimental floodplain in 2002; 0.6% in 2005), and increasing exponentially (see “intrinsic population dynamics” below), we assumed that the dynamics of the entire study area population would experience negligible density-dependent interference. This perennial weed has discrete generations with annual growth and reproduction culminating in summer, which was when we measured population parameters. Thus, we analyzed the annual rate of increase of discrete generations without density dependence using the equations:

$\lambda = N_{t+1}/N_t$ OR $R_0 = N_{t+1}/N_t$

$r = \ln \lambda$

where λ is the annual rate of increase and r is the intrinsic rate of natural increase of the population.

Using collected data from years 2002 - 2005, we calculated the average intrinsic annual rate of increase of tillers, area, and density within patches. Data were transformed to meet assumptions of normality for parametric statistical testing. Annual *Lepidium* patch data (i.e., tillers, area, density) were normalized using a natural logarithm transform. We related these population data to environmental predictors to determine if growth rates were affected by intrinsic population dynamics, floodplain position (i.e., elevation, slope, aspect), and other prominent landscape features, such as distance to roads, levees, and water features.

Spatial distribution of new invasions and disappearing populations

sing these same monitoring and GIS data, we isolated "missing" patches from patches extent for all four years to enable analysis of differences in their relative spatial locations. We defined missing patches as those patches present in 2004 which were untreated by any means and which were absent in 2005. We defined as "surviving" those patches present in 2004 which were untreated by any means and which were present in 2005. We used parametric (one-way ANOVAs and t-tests) and non-parametric (Wilcoxon) tests to examine the spatial and population data of these two subsets for potentially significant and explanatory differences. (e.g., distance to environmental factors, often normalized through natural log transformations) using a nominal logistic model. We used the resulting predicted response equation (probability of missing) to graph the predicted fate of patches based on true distance to the environmental factor in question.

We defined "new" patches as those patches inventoried in 2005 which were not inventoried in 2004 or 2002, and those patches inventoried in 2004 which were not inventoried in 2002. We combined these two data subsets (new in 2004 and new in 2005). Because we did not conduct a complete inventory in 2003, but only re-surveyed 2002 populations, information from this year was not relevant to the definition of new patches. As above, we defined as "surviving" those patches present in 2004 which were untreated by any means and which were present in 2005. Again, we compared the spatial and population data of these two subsets using parametric (one-way ANOVAs and t-tests) and non-parametric (Wilcoxon) tests.

Results & Key Findings

Intrinsic Population Dynamics

Perennial pepperweed patches originally inventoried in 2002 were monitored for four years to establish patterns of intrinsic population dynamics. Of the original 157 patches of pepperweed inventoried in 2002, twenty-five (25) were excluded from analysis due to treatment (pulling or breaking of tillers, or inclusion in a pilot control project). Of the remaining 132 patches, four (4) were not relocated in 2003, one (1) was not relocated in 2004, and nine (9) were not relocated in 2005. Thus, for the purposes of measuring trends in population dynamics, analyses were run on the 123 patches which persisted over all four years.

Tiller number and patch size increased from 2002-2005, but tiller density remained the same throughout this time period. In the 127 *Lepidium* patches monitored annually from 2002 through 2005, tiller numbers and patch area significantly increased as time progressed (Figures 2-4, Tables 2-4).

The process of invasion is characterized by three phases: introduction, colonization, and naturalization (Groves 1986). In its introduction and colonization phase, weed spread typically follows one of two population trajectories: a two-phase increase with an initial lag phase followed by exponential increase, or an immediate exponential increase (Cousens and Mortimer 1995). The type of trend exhibited is important for the development and prioritization of weed control strategies. An initial lag phase is typically characterized by a constant rate of spread, in which patch area increases as a function time squared, yielding a linear fit of the square root of area against time. Exponential growth patterns yield a linear fit when regressing log area against time.

Based on four years of monitoring, areal expansion of established patches of perennial pepperweed at our site appears to be following a pattern of exponential growth (Figure 5, Table 5).

Rate of expansion

The growth rate in tiller number is highest in patches with lower initial stem numbers, and decreases as stem number increases (Figure 6). We calculated the annual intrinsic rate of tiller expansion, $(\ln(\text{TILLERS}_{2005}+1)-\ln(\text{TILLERS}_{2002}+1))/(2005-2002)$ and tested this against the natural log of tillers per patch in 2002, $\ln(\text{TILLERS}_{Y}+1)$. This regression yields a negative correlation between intrinsic rate of annual tiller increase and initial number of tillers per patch (Table 6).

The growth rate for patch area is also highest in small patches (Figure 7). We calculated annual intrinsic rate of areal expansion as above and tested this against the natural log of area per patch in 2002. The resulting negative regression was, again, highly significant (Table 7), but explained less of the variance than initial tiller count on rate of patch expansion.

Change in density

Patches with lower initial stem densities tended to have positive annual rates of density increase, while patches with higher initial tiller densities tended to have decreasing densities over time (Figure 8). This trend is explained by the fact that, as new tillers colonize outer edges of the invasion front, the area of the patch increases. While tillers in the center of the patch remain dense, increasing the patch perimeter to include new, sparse outlier tillers decreases the overall tiller density of the patch. Tiller density was calculated as tillers per patch per patch area, and intrinsic rate of tiller density increase was calculated as above. The regression of intrinsic rate of annual tiller density increase against initial tiller density per patch is highly statistically significant (Table 8).

Extrinsic Population Dynamics

Disappearing patches

Not all patches of perennial pepperweed persisted throughout the four years of this study. Seven (7) of the original 157 patches identified in 2002 were not relocated in 2003. Of these, six (6) were relocated in 2004, indicating that either a new colony established within 1 meter of the original colony, or that the original colony persisted but was missed in the field inventory of 2003. Assuming that these patches were missed in the field, 96% of the original patches were found in 2003. All patches identified in 2003 were relocated in 2004, representing a 100% detection rate of original patches in this year. Of the 443 patches inventoried in 2004, 332 were relocated in 2005. The 111 unrepresented patches were either removed by treatment, in this case pulling (14 patches) or breaking (5 patches) of tillers; removed by roadside mowing (1); discounted from our inventory because they became part of a new pilot control program (38 patches); misclassified as "disappeared" in 2005 due to its >2 meter distance from the prior year's point (1), overlooked in the field, or disappeared due to natural causes. Based on the 2002-03 detection rate of 96%, we estimate that 2 patches were likely overlooked due to field error, the remaining 50 being removed by scour, burial by sand deposits, or other natural means. Our conclusion is supported by our field methodology, which is based on sub-meter accuracy GPS units used to re-survey and search for previously established patches.

We hypothesize many of the 52 patches missing in 2005 without explanation were removed by scour and/or sand deposits, due to their close proximity to floodplain features that promote dynamic geomorphic processes. This is supported by the significantly shorter distance between active inflow breaches and disappeared patches compared to surviving patches (Wilcoxon χ^2=9.99; P=0.0012), and the higher chance of patch disappearance closer to active input breaches (Figure 9). Using the probability formula computed from the logistic fit of patch fate to the log-transformed distance to active inflow breaches, it was predicted that 10 of the 443 patches present in 2004 would disappear in 2005 due to their proximity active inflow breaches.

Of these 10 patches, five actually disappeared in 2005. We hypothesize that most unexplained patch disappearances were also a result of scour and burial by sand, due to their location directly downstream of active inflow breaches in areas which experience high velocity flows during flooding events (Figure 10).

New patch establishment

Compared with those patches which survived throughout the four years of this study, new patches of *Lepidium* inventoried in 2004 and 2005 tended to establish in locations closer to flowing water (Figure 11), especially closer to levee breaches (Figure 12) and to the upstream (north) end of the floodplain (Figure 13), suggesting that new populations are being spread primarily by transportation of propagules by water sources. No relationship was found between new patch establishment and distance to road, which indicates that roads, in this case, are not a significant propagule vector. This is not surprising, considering that the floodplain is accessible only to Preserve staff, adjacent rice farmers, and researchers, and thus the adjacent levee roads do not experience a high volume of traffic. There was also no significant difference between elevation of old and new patches, indicating that new patch invasion is taking place in areas with similar topography to those areas already invaded in prior years.

Although we had originally hypothesized that canopy cover may inhibit Lepidium establishment and growth, no correlation was found between canopy cover and new patch establishment. These results are of concern to managers, as original expectations had been that, as restoration progresses and riparian forests become established, canopy cover would shade and thus preclude the spread of Lepidium.

Growth rate

Growth rates were found to be highest in upstream areas and areas at intermediate distances to active river and slough channels. Annual growth rates of tillers and patch areas, and rate of density increase, were faster in the northern, upstream section of the restored floodplain (Figures 14, 15 and 16). Tiller growth rates and rate of density increase were inhibited in patches located directly adjacent to or at far distances from active slough or river channels (Figures 17 and 18). These results are compatible with the observation that areas at intermediate distances from high velocity inflow paths are situated at ideal locations for moderate levels of floodwater inundation and the subsequent settling of nutrient-loaded sediment and plant propagules.

Our results indicate that distance to flowing water and levee breaches are more important regulators of patch dynamics than distance to roads. Patches closer to roads had lower rates of tiller increase and patch expansion than those further from roads (rTillers x log(Distance to road) Linear Fit R^2 = 0.046771, p = 0.0163; rPatchArea x log(Distance to road) Linear Fit R^2 = 0.064252, p = 0.0047). This may be due to road-related disturbance, but is more likely due to the fact that, as distance to roads increases, distance to waterways and breaches decreases.

Rate of spread within established patches is correlated with distance to breach, but appears to be relatively constant within an approximately 250 m radius “breach impact” zone, decreasing beyond this zone. Rates of patch area expansion and tiller increase were highest within the classified breach impact areas (zones defined as being 250 m downstream from levee breaches), decreasing with distance to these zones (rTillers x Log(Breach Impact Distance) Linear Fit R^2 = 0.065114, p = 0.0044; rPatchArea x Log(Breach Impact Distance) Linear Fit R^2 = 0.051658, p = 0.0115). As described above, distance to active inflow breach, measured as a continuous variable, was highly significant in explaining the locations of new patch establishment and patch disappearance, indicating that rates of patch turnover are highly sensitive to small changes in distance to the nearest inflow breach. No correlation was found between these same distance measurements and the rates of patch area or tiller increase, however, indicating that growth rates of established patches are subject to breach impact effects, but are not as sensitive to these effects as is rate of patch turnover.

Considering the range of inundation regimes experienced by Lepidium patches on the floodplain, growth rates are highest in areas with greater soil moisture due to longer inundation times. Tiller and area expansion were fastest at lower elevations within the range of elevations occupied by perennial pepperweed (rTillers x 2002elevation Linear Fit R^2= 0.067326, p = 0.0038; rPatchArea x 2002elevation Linear Fit R^2= 0.042149, p = 0.0227). Elevation on the floodplain is indicative of microtopographic differences which manifest variations in duration of inundation following flood events. No patches of *Lepidium latifolium* are located within ponds (see Figure 19), which is consistent with reports that *Lepidium* is not capable of withstanding highly extended periods of inundation (Chen, Qualls et al. 2002).

Canopy cover in 2002 made no difference in the rates of tiller or patch area expansion. Rate of density increase tended to be higher with increasing canopy cover modeled continuously (p=0.007); however, this positive relationship explained only 5% of the variance. This positive relationship also held when modeled logistically using some cover versus no cover (χ^2=3.66; P=0.056; ROC AUC=0.66).

Recommendations for management and monitoring

Populations of *Lepidium latifolium* are increasing rapidly in the Cosumnes River Preserve's restored floodplain, with only minor variability in rate of spread across the landscape. Introductions appear to be from both roads and breaches, and have the potential to spread quickly and dominate open areas and the understory of the rapidly expanding floodplain forests. Although we found that perennial pepperweed patches were most likely to be eliminated in large flood events, relying on scour and deposition to control pepperweed populations is not advised; pepperweed patches need to be within 16m of an active inflow levee breach to have greater than a 50% chance of being completely destroyed. Even then, the fate of the uprooted plants is unknown, but some transported root fragments probably successfully colonize new sites.

Control measures should be implemented and evaluated to slow the expansion of this invasive species so as to allow the natural succession of native species in this restored floodplain. Alternative control methods are currently being tested in a joint project between TNC and UC Davis, and will inform adaptive weed management programs at the Preserve. Concurrently, ground-based inventories of management sites are underway. We recommend continuation of these two efforts, and encourage the use of advanced spatial technologies to identify coarser-scale establishment and subsequent spread over time. The use of such technology for non-native species mapping is now robust, and can be used to generate inventory maps for prioritization of control efforts over large spatial areas.

Other recommendations for management and monitoring of *Lepidium* include the development of probability surface models that predict future invasion. A variety of statistical models are currently being tested for this purpose. In general, they use regression-like analyses based on relationships between existing Lepidium locations and absence points and relevant predictors, such as soil type, neighboring vegetation type, elevation, distance to disturbance vector, and proximity to former invasion. These models can be correlated with remotely sensed imagery, and derivative measures of plant vigor, to provide a more synoptic view of *Lepidium* invasions that can be applied to other areas within the aegis of CALFED. As such, we recommend the use of high spatial resolution remote sensing for extensive monitoring of non-native plant invasions. Advances in the use of lidar – light detection and ranging or laser altimetry – and hyperspectral sensors have reduced the resolution of most data products to better than 1m on the ground. Lidar provides detailed structural measurements – often more than seven laser measurements per square meter that are better than 10cm in vertical accuracy – that can be constructed to depict microtopographic relief and plant canopy structure over thousands of hectares. Hyperspectral imagery allows for the identification of many constituents, such as flowering non-native species or dead and dying plant communities, in addition to geomorphically important substrates such as sands and gravels. These types of remote sensing can be conducted on fixed intervals (e.g., yearly) or during time sensitive events (e.g., floods) as robust form of monitoring.

Conclusions

We studied the invasion of a non-native plant onto the Cosumnes River experimental floodplain to help determine, which, if any, landscape factors promote its invasion. As part of this process, we followed its population dynamics to better understand its habit. Understanding the invasion process, especially the phases of introduction, colonization, and naturalization, helps determine appropriate remediation. Weeds typically spread through a two-phase increase with an initial lag followed by exponential increase, or an immediate exponential increase. The type of expansion trend exhibited is important for weed control strategies in that it helps gauge the amount of time available to leverage resources against the invasion. Based on four years of monitoring, expansion of established patches of perennial pepperweed at our site appears to be following a pattern of exponential growth throughout the floodplain, with growth rates highest in areas with relatively high soil moisture. New patch establishment, and some patch turnover, is generally found closer to levee breaches, which serve as vector sources and areas subject to scour and sand deposition. In addition to further research on the ecology of perennial pepperweed, we recommend early eradication of emerging populations on a regular basis to prevent the naturalization of this weed within this and other restoration sites.

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Figure 1. Cosumnes River Preserve Experimental Floodplain location.

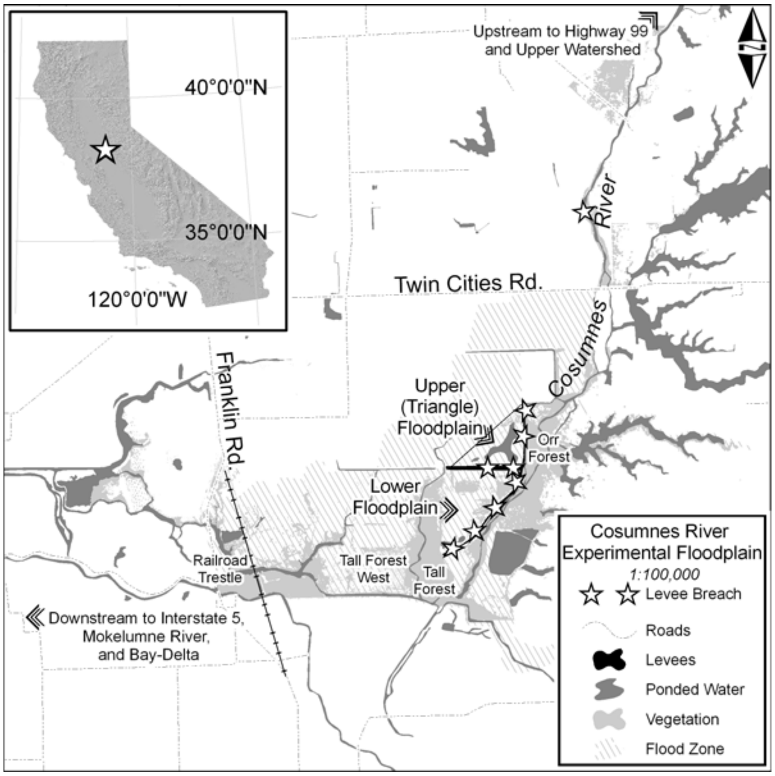

Table 1. Patch threshold distance enforcement through recursive buffering.

GPS Patches Merged using recursive buffering (+/- 3 meters)								
Merged GPS patches	Count (2002)	Count (2003)	Count (2004)	Count (2005)	PctOfTotal (2002)	PctOfTotal (2003)	PctOfTotal (2004)	PctOfTotal (2005)
1	142	138	383	330	90%	88%	86%	90%
2	10	12	35	29	6%	8%	8%	8%
3	2	4	12	5	1%	3%	3%	1%
4	2	2	6	3	1%	1%	1%	1%
5	1	0	4	1	1%	0%	1%	0%
6	0	0	1	0	0%	0%	0%	0%
7	0	0	1	0	0%	0%	0%	0%
13	0	0	1	0	0%	0%	0%	0%

Figure 2. Stems Per Patch 2002 – 2005. (Includes only those patches in which no weed control efforts were undertaken. For visual clarity, values >1000 stems/patch are included in statistics but not visible in the graph below.)

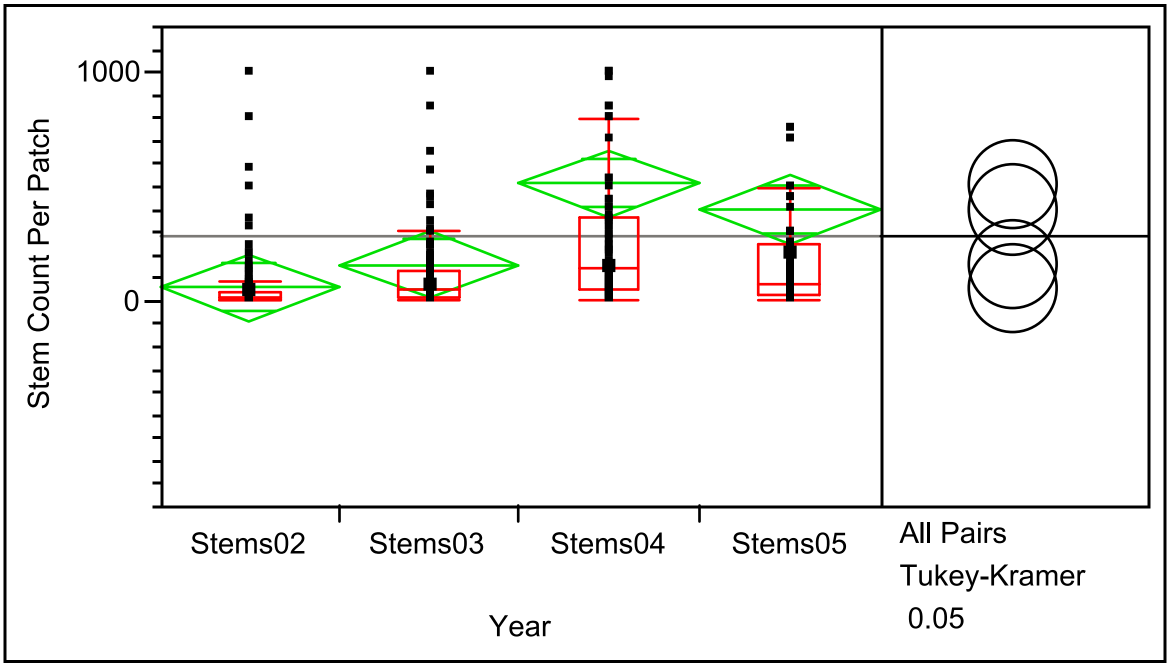

Table 2. Stems Per Patch 2002 – 2005. Comparisons for all pairs using Tukey-Kramer HSD. Levels not connected by same letter are significantly different.

Level				Mean (stems/patch)
Stems04	A			514.01626
Stems05	A	B		400.62602
Stems03		B	C	161.42975
Stems02			C	58.17886

Figure 3. Area Per Patch 2002 – 2005. (Includes only those patches in which no weed control efforts were undertaken. For visual clarity, values >400 m^2 are included in statistics but not visible in the graph below.)

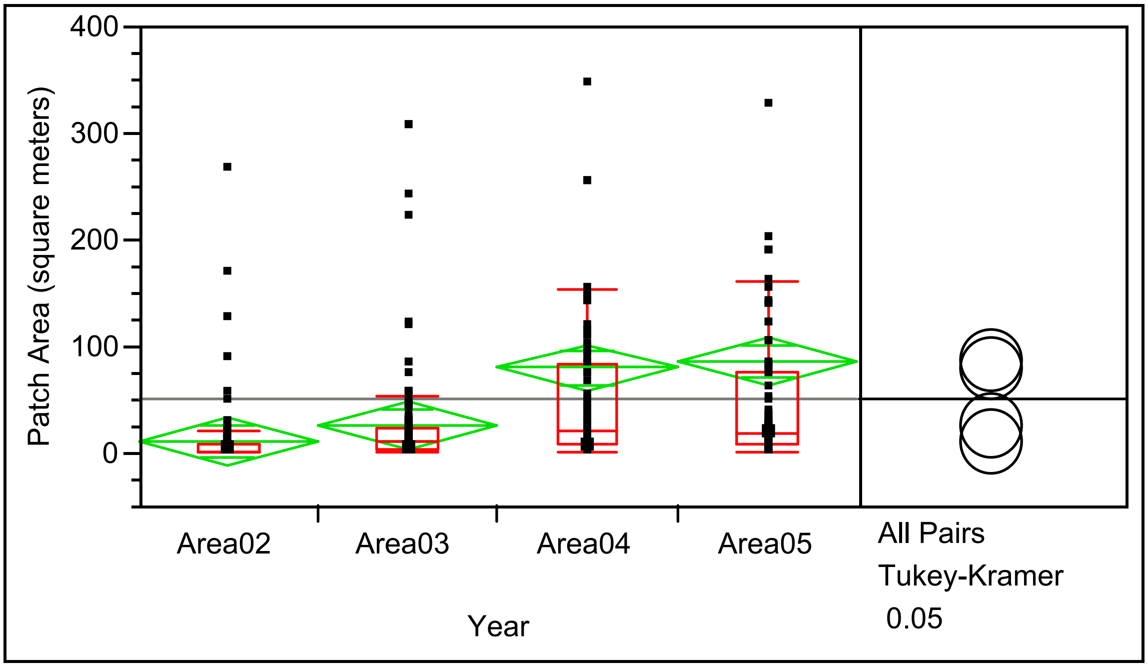

Table 3. Area Per Patch 2002 – 2005. Comparisons for all pairs using Tukey-Kramer HSD. Levels not connected by same letter are significantly different.

Level			Mean (m^2 per patch)
Area05	A		86.598211
Area04	A		80.266911
Area03		B	26.094876
Area02		B	11.271545

Figure 4. Stem Density Per Patch 2002 – 2005. (Includes only those patches in which no weed control efforts were undertaken. For visual clarity, values >50 stems/m^2 are included in statistics but not visible in the graph below.)

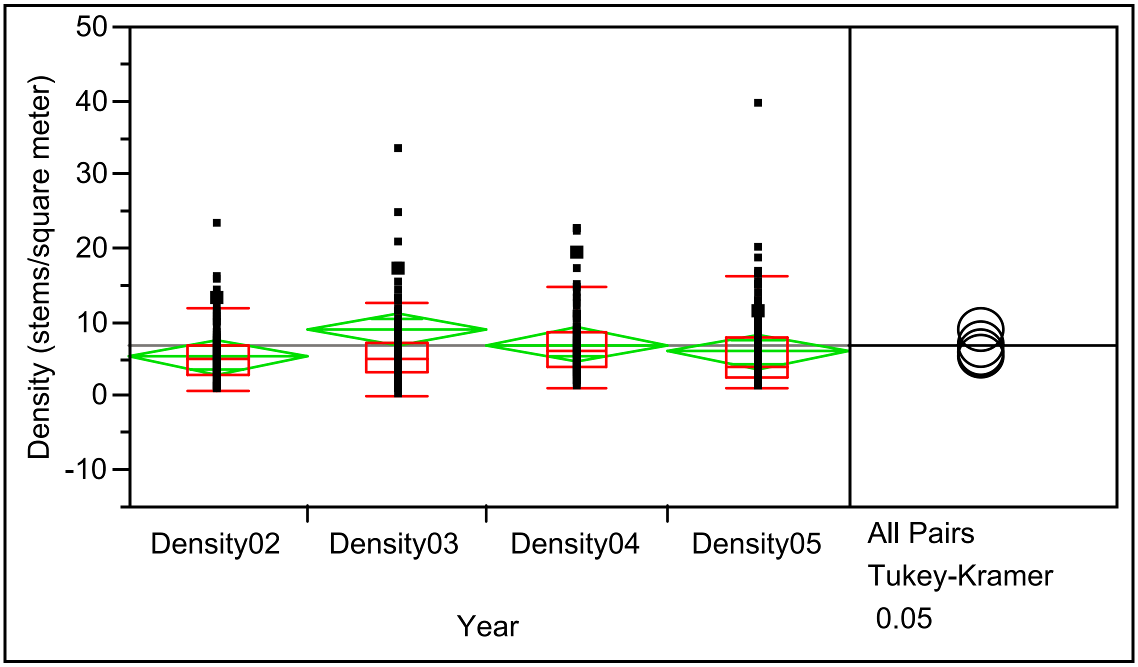

Table 4. Stem Density Per Patch 2002 – 2005. Comparisons for all pairs using Tukey-Kramer HSD. Levels not connected by same letter are significantly different.

Level		Mean (stems/m^2 per patch)
Density03	A	8.9961715
Density04	A	6.9473304
Density05	A	5.9507021
Density02	A	5.3478666

Figure 5. Exponential growth rate of patch area from 2002 – 2005. Data from 123 patches monitored annually from 2002 to 2005. (Includes only those patches in which no weed control efforts were undertaken.)

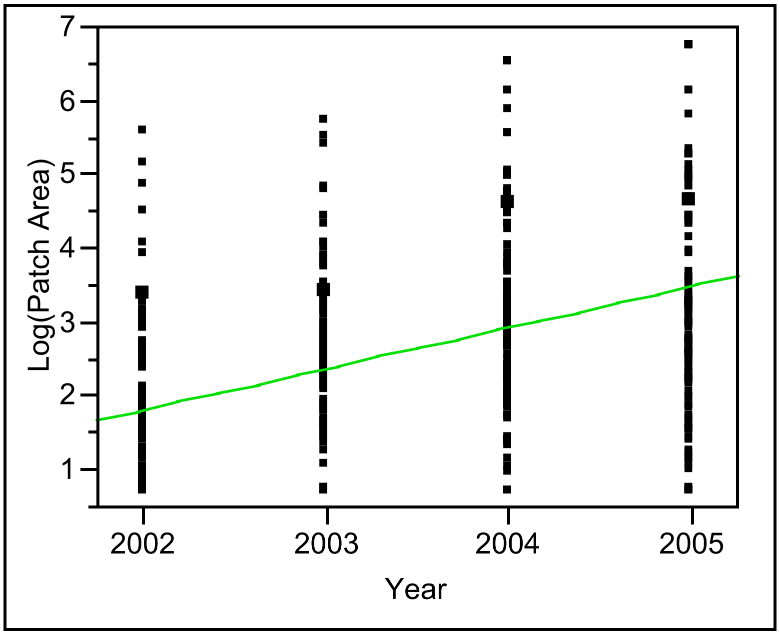

Table 5. Exponential growth rate of patch area from 2002 – 2005.

Linear Fit
ln_patch_area = -1115.925 + 0.5583082 Yr

Summary of Fit

RSquare	0.176812
RSquare Adj	0.175125
Root Mean Square Error	1.351817
Mean of Response	2.646063
Observations	490

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	191.5439	191.544	104.8172
Error	488	891.7760	1.827	Prob > F
C. Total	489	1083.3199		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1115.925	109.2566	-10.21	<.0001
Yr	0.5583082	0.054533	10.24	<.0001

Figure 6. Intrinsic annual rate of tiller increase as a function of intial (2002) tiller number. Intrinsic annual rate of tiller increase calculated from number of tillers/patch in 2002 and 2005. (Includes only those patches in which no weed control efforts were undertaken.)

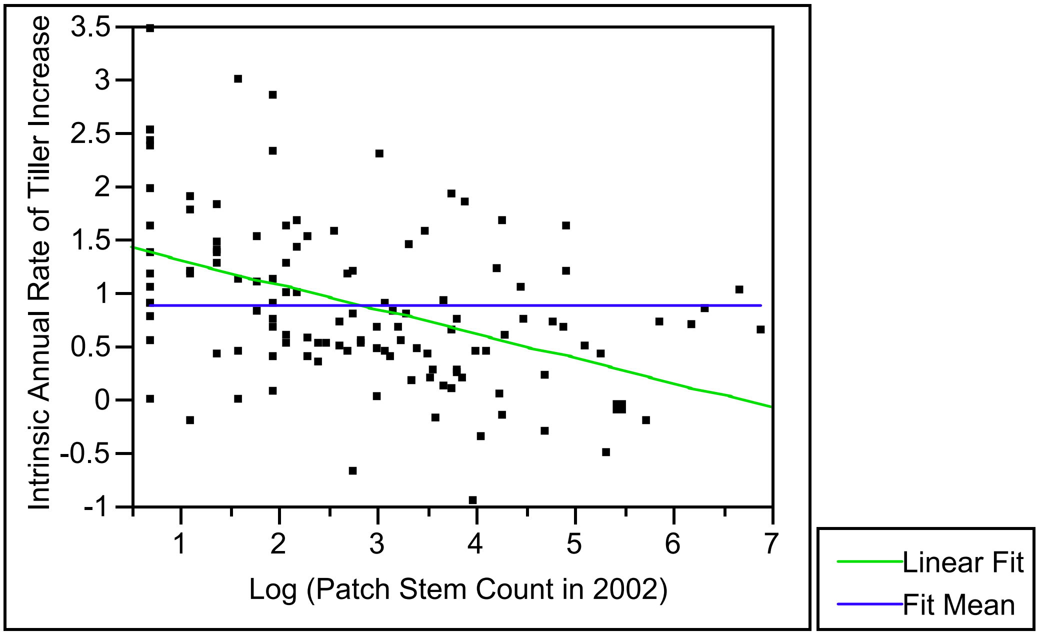

Table 6. Intrinsic annual rate of tiller increase as a function of intial (2002) tiller number.

Linear Fit
rStems02to05 = 1.5420147 - 0.2292831 ln_Stems02

Summary of Fit

RSquare	0.194999
RSquare Adj	0.188346
Root Mean Square Error	0.712917
Mean of Response	0.89716
Observations	123

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	14.897018	14.8970	29.3104
Error	121	61.498348	0.5083	Prob > F
C. Total	122	76.395366		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.5420147	0.13535	11.39	<.0001
ln_Stems02	-0.229283	0.042351	-5.41	<.0001

Figure 7. Intrinsic annual rate of areal increase as a function of intial (2002) patch area. Intrinsic annual rate of areal increase calculated from area per patch in 2002 and 2005. (Includes only those patches in which no weed control efforts were undertaken.)

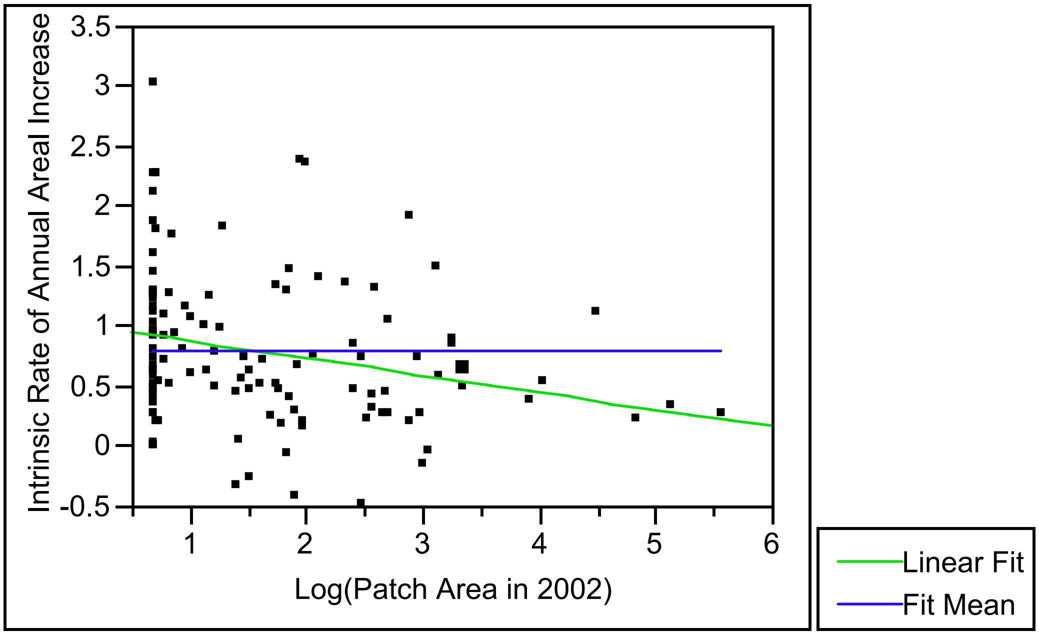

Table 7. Intrinsic annual rate of areal increase as a function of intial (2002) patch area.

Linear Fit
rArea02to05 = 1.0217286 - 0.1419791 ln_Area02

Summary of Fit

RSquare	0.053203
RSquare Adj	0.045378
Root Mean Square Error	0.655039
Mean of Response	0.793445
Observations	123

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2.917431	2.91743	6.7993
Error	121	51.918207	0.42908	Prob > F
C. Total	122	54.835638		0.0103

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.0217286	0.105607	9.67	<.0001
ln_Area02	-0.141979	0.054449	-2.61	0.0103

Figure 8. Intrinsic annual rate of density increase as a function of intial (2002) stem density per patch. Intrinsic annual rate of density increase calculated from patch area and stem data in 2002 and 2005. (Includes only those patches in which no weed control efforts were undertaken.)

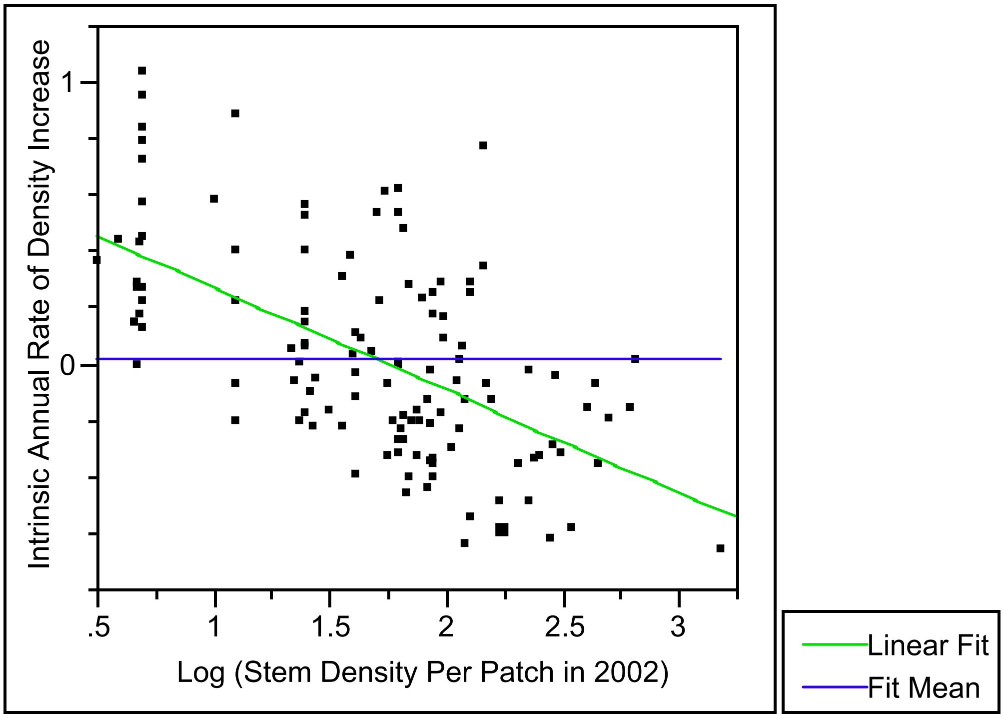

Table 8. Intrinsic annual rate of density increase as a function of intial (2002) stem density per patch.

Linear Fit
rDensity02to05 = 0.635489 - 0.3628538 ln_density02

Summary of Fit

RSquare	0.343159
RSquare Adj	0.33773
Root Mean Square Error	0.298255
Mean of Response	0.02437
Observations	123

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	5.623348	5.62335	63.2150
Error	121	10.763667	0.08896	Prob > F
C. Total	122	16.387015		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.635489	0.081432	7.80	<.0001
ln_density02	-0.362854	0.045637	-7.95	<.0001

Figure 9. Probability of patch survival or disappearance as a function of distance to an active input breach. Dotted lines indicate the 50% probability mark, which corresponds to approximately 16 meters from an active inflow breach. Red points indicate the probability of surviving exposure to active inflow breach dynamics. Green points indicate the probability of not surviving exposure to active inflow breach dynamics.

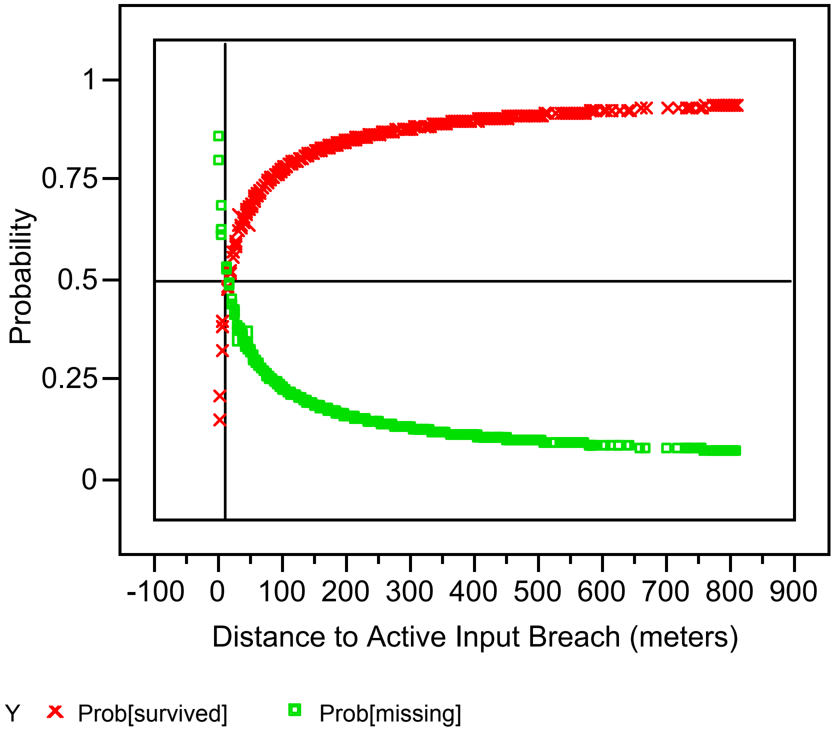

Figure 10. Map of missing patches (those not explained by treatment or other known causes) on the experimental floodplain. Circle size indicates number of tillers present in 2004, before the patch became missing in 2005.

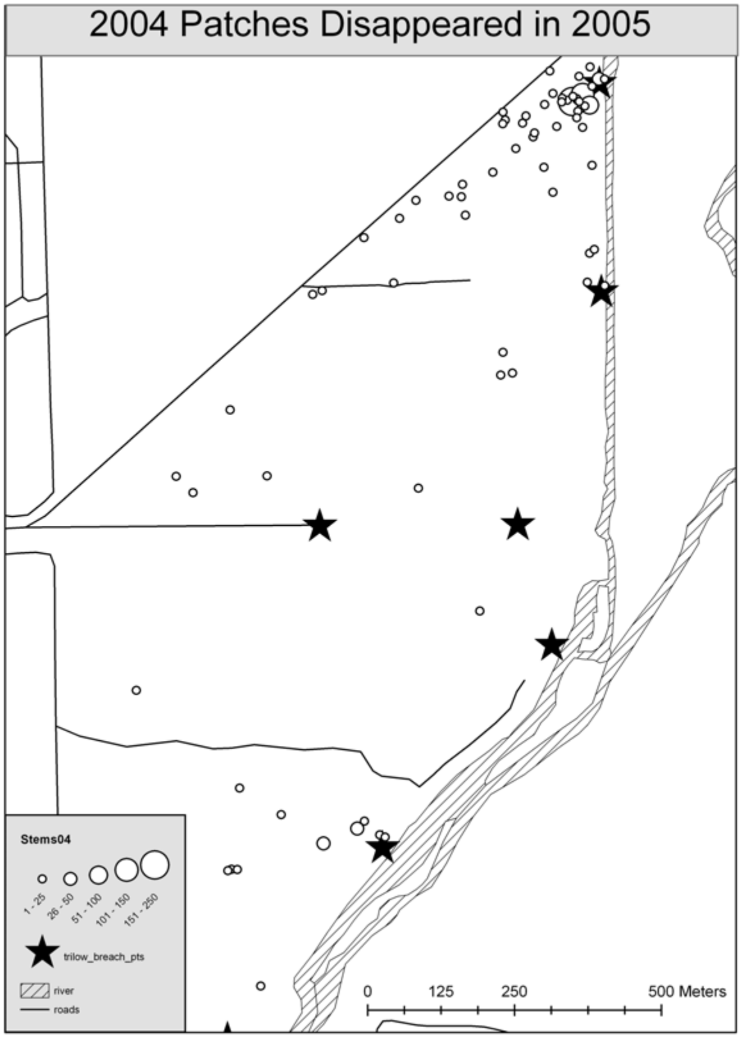

Figure 11. New *Lepidium* patches tend to be located closer to flowing water (rivers or sloughs) than older, established *Lepidium* patches. (T test p = 0.0094, Wilcoxon Rank Sum Prob > Chi-Square 0.0101)

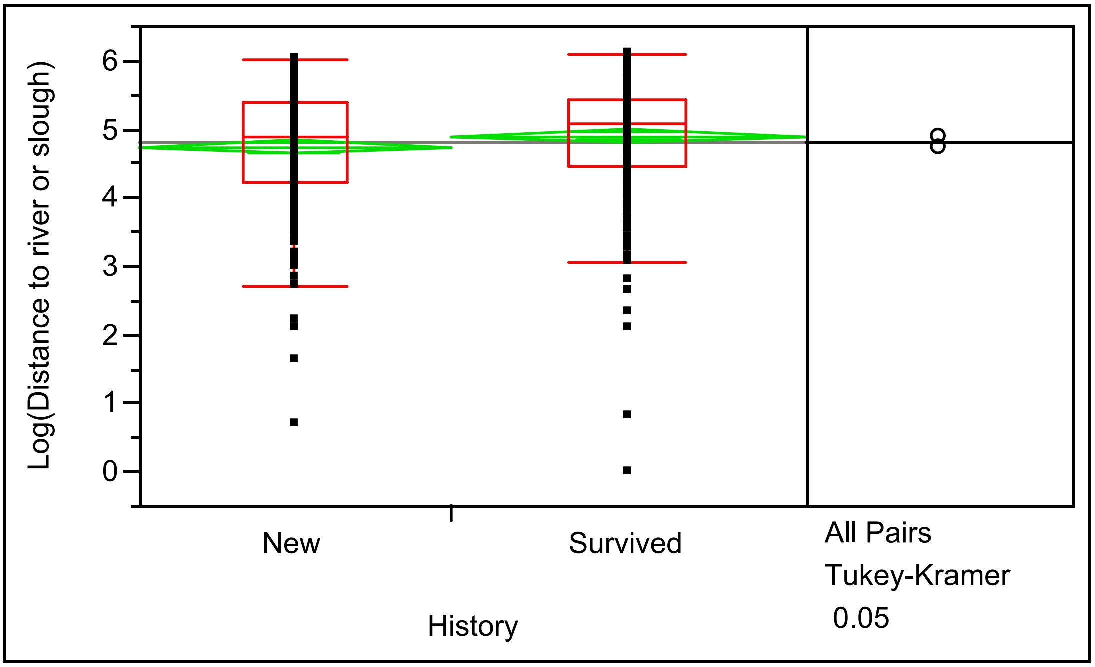

Figure 12. New *Lepidium* patches tend to be located closer to active inflow breaches than older, established *Lepidium* patches. (T test Prob < t 0.0003)

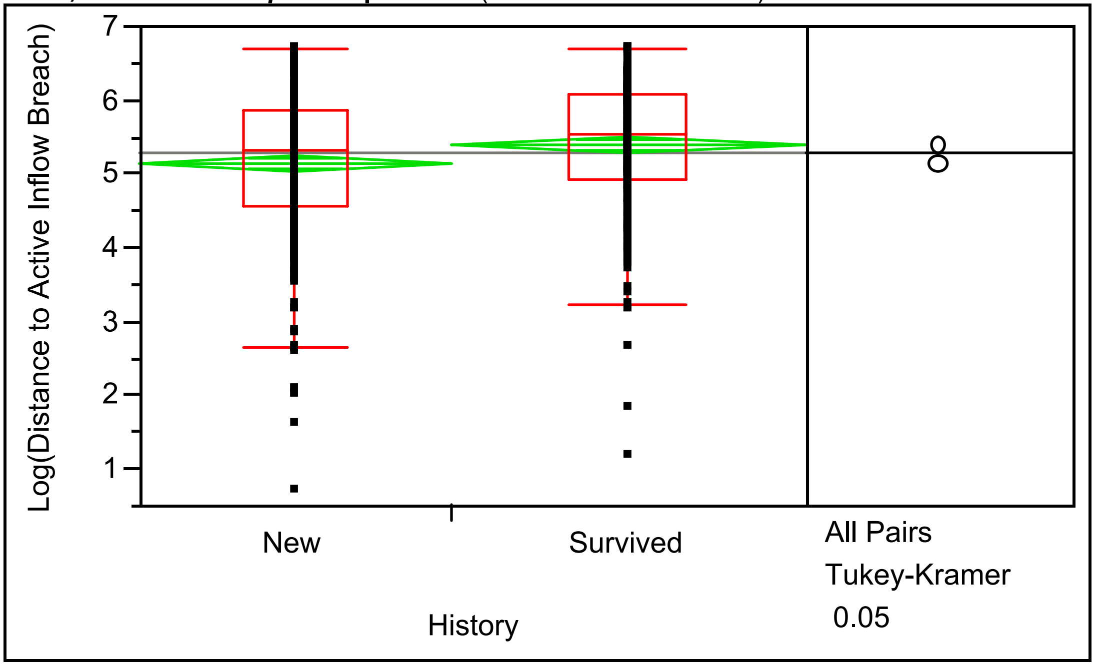

Figure 13. New *Lepidium* patches tend to be located further upstream (further north) than older, established *Lepidium* patches. The Y axis in this graph represents latitude (labeled Y) as measured in a Universal Transverse Mercator (UTM) projection (Zone 10 N; NAD83) in meters. (Wilcoxon Rank Sum Prob > Chi-Square 0.0022)

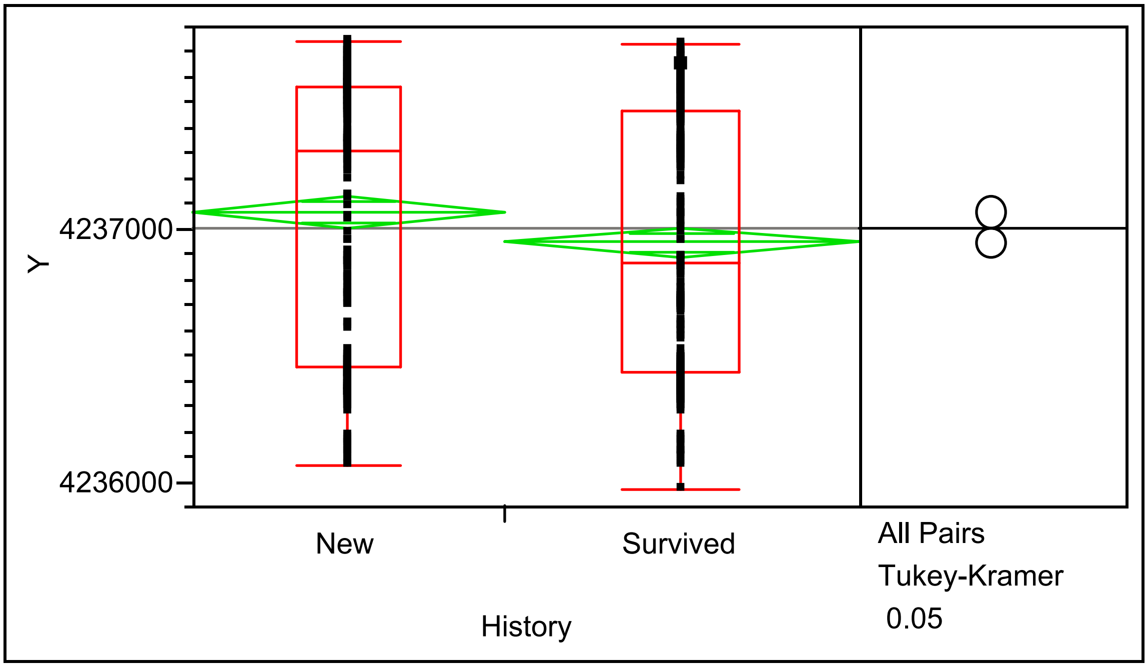

Figure 14. Tiller growth rates are higher further upstream (further north) within the floodplain Latitude is measured in a Universal Transverse Mercator (UTM) projection (Zone 10 N; NAD83) in meters. (rTillers x Latitude Linear Fit $R^2 = 0.253948$, $p < 0.0001$).

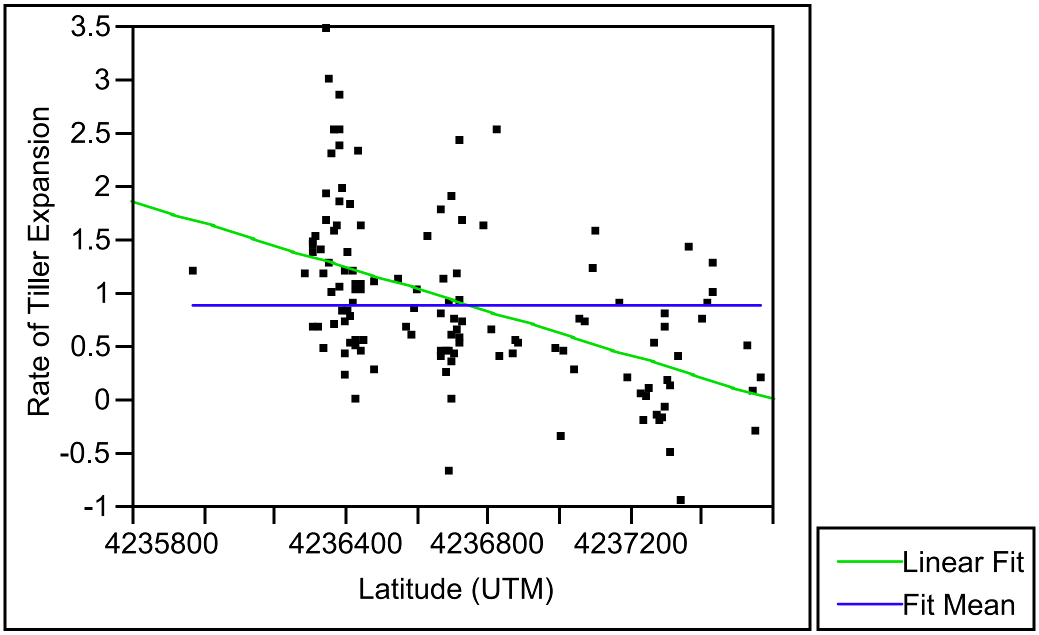

Figure 15. Patch area growth rates are higher further upstream (further north) within the floodplain Latitude is measured in a Universal Transverse Mercator (UTM) projection (Zone 10 N; NAD83) in meters. (rPatchArea x Latitude Linear Fit R^2 = 0. 115607, p = 0.0001).

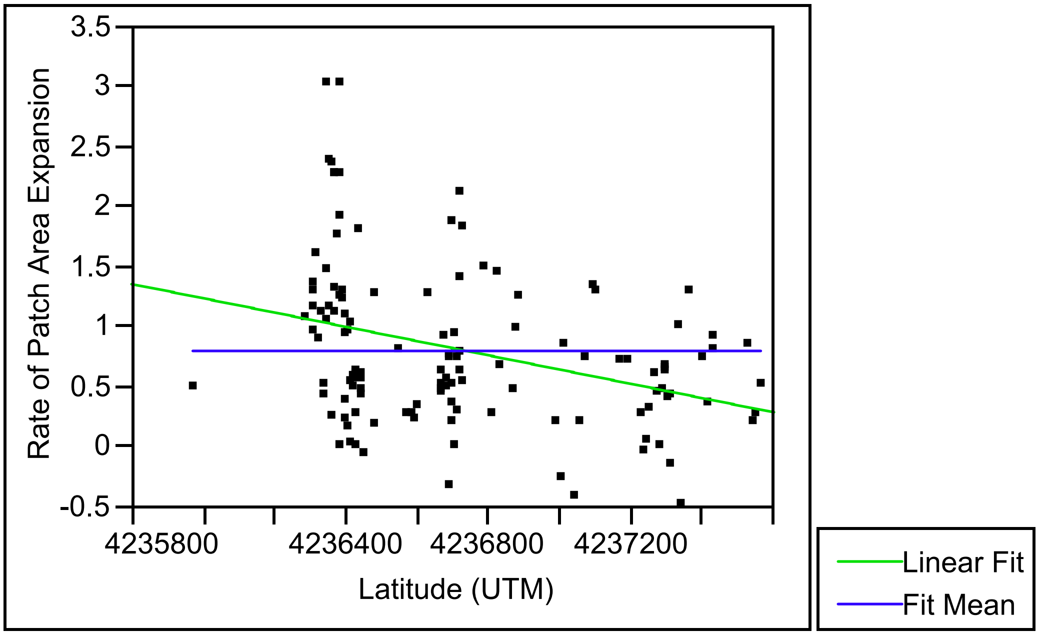

Figure 16. Rates of density increase are higher further upstream (further north) within the floodplain Latitude is measured in a Universal Transverse Mercator (UTM) projection (Zone 10 N; NAD83) in meters. (rDensity x Latitude Linear Fit R^2 = 0.111997, p < 0.0001).

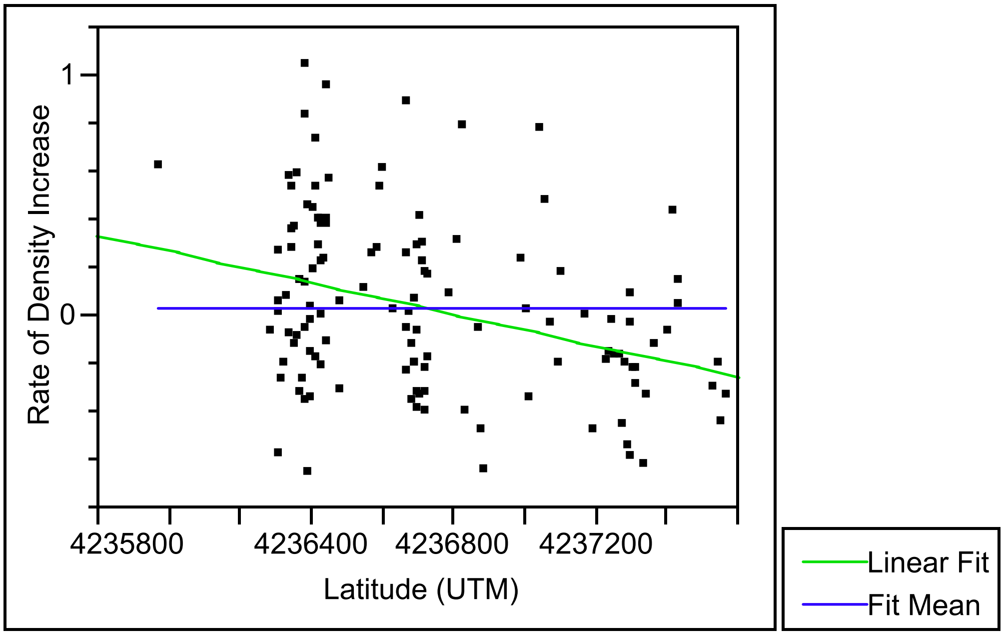

Figure 17. Tiller expansion rates are highest at intermediate distances from river or slough channels. Distance to river or slough is measured in log(meters). (rTillers x Log(Distance to river or slough) Quadratic Fit R^2 = 0.07559, p = 0.0090).

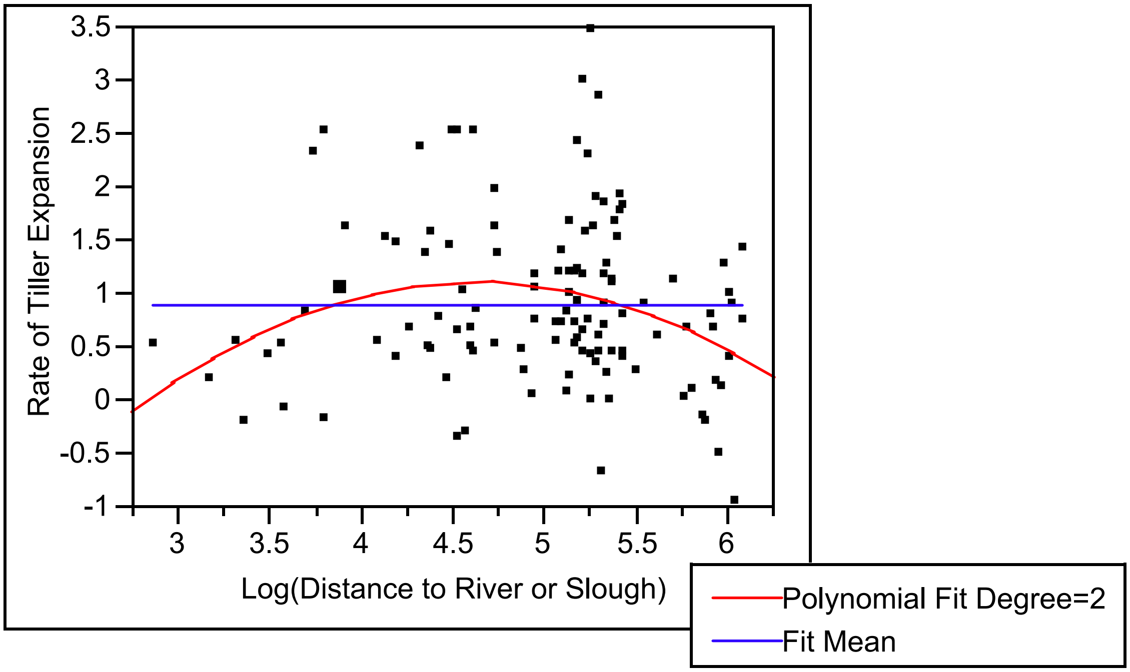

Figure 18. Rates of density increase are highest at intermediate distances from river or slough channels. Distance to river or slough is measured in log(meters). (rDensity x Log(Distance to river or slough) Quadratic Fit R^2 = 0.084438, p = 0. 0050).

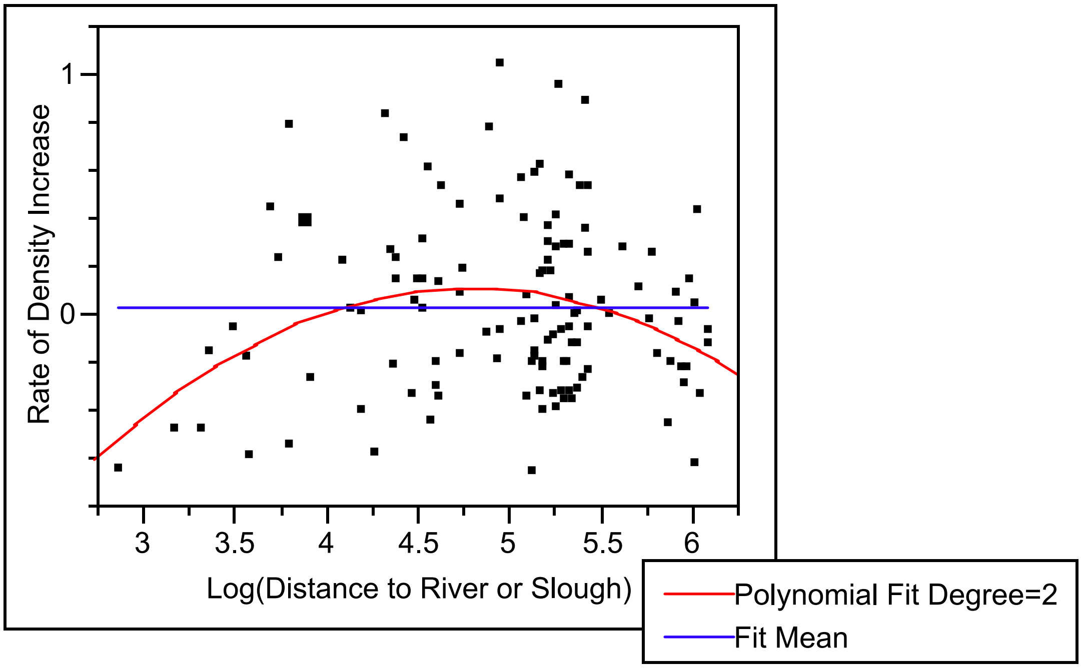

Figure 19. Intrinsic annual rate of *Lepidium latifolium* patch area growth at all original 2002 inventory patches which were untreated and survived through 2005.