

1                   **Comparison of thinning and prescribed fire restoration treatments to**  
2                   **Sierran mixed-conifer historic conditions**

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13 **Abstract:** After a century of fire suppression, mechanical thinning and prescribed fire  
14 are widely used restoration treatments for Sierran mixed-conifer, yet there have been few  
15 studies of how effective these treatments are at restoring the diameter distribution,  
16 species composition or spatial structure of forests with an active fire regime. We  
17 examined forest structure and composition before and after treatments on 18 replicated 4  
18 ha plots against a reconstruction of stand conditions in 1865, the year of the last extensive  
19 fire at our study area. We measured, mapped and tagged all stems and logs in the 72 ha  
20 experiment before and after applying a full-factorial design of treatments crossing  
21 thinning (none, understory and overstory thinning) with burning (no burn and prescribed  
22 fire) on three replicates of each treatment. Stand structure and composition in 1865 were  
23 reconstructed using a sample of aged trees, their growing spacing, and annual basal area  
24 increment growth, and applying derived equations to stem maps of all trees, snags and  
25 logs. Historic stand structure averaged 67 stems/ha (trees  $\geq 5$  cm dbh), was 51% shade  
26 tolerant (*Abies concolor*, *A. magnifica*, and *Calocedrus decurrens*) and 49% shade  
27 intolerants (*Pinus Jeffreyi* and *P. lambertiana*), stems were slightly clustered at small  
28 scales and randomly distributed at the stand scale, and had a diameter distribution that  
29 was fairly flat across all size classes. The pretreatment forest significantly differed  
30 averaging 469 stems/ha which were 84% shade tolerant and 14% shade intolerants, was  
31 highly clustered, and had a diameter distribution that followed a reverse J-shape curve.  
32 Thinning treatments reduced stand density, but failed to approximate historic species  
33 composition, spatial pattern or diameter distribution. Prescribed fire only significantly  
34 altered stand structure and composition when used with thinning, probably because the  
35 late-fall prescribed fire had little impact without additional fuels provided by thinning.

36 All restoration treatments left too many small trees (5-25 cm dbh) and removed too many  
37 intermediate-size trees (50-75 cm dbh) shifting down but still retaining the current  
38 reverse J-shaped diameter distribution. All thinning treatments significantly reduced  
39 basal area and quadratic mean diameter below historic levels. Current old growth (pre-  
40 treatment) has fewer large trees (> 100 cm dbh) than historic conditions, suggesting  
41 restoration treatments may need to retain more intermediate-size trees to provide for  
42 future large tree recruitment. Combined thinning and fire treatments had the greatest  
43 impact on reducing stem density particularly in the small diameter classes, and  
44 understory thinning and prescribed fire produced a spatial pattern closest to our historic  
45 reconstruction. Our experiment suggests effective restoration in mixed-conifer may  
46 require thinning prescriptions that vary by species and flexible rather than rigid upper  
47 diameter limits to retain some trees in all size classes.

## 48 **Introduction**

49 Sierran mixed-conifer forest, primary habitat for more vertebrate species than  
50 any other forest community in California (Mayer and Laudenslayer 1989), has been  
51 severely altered from a century of fire suppression. Historically these forests had a mean  
52 fire return interval of 12-17 years which has now shifted to more than 600 years by one  
53 estimate (McKelvey et al. 1996). Regional plans (SNFPA 2004) and national policies  
54 have general restoration guidelines typified by language in the Healthy Forests  
55 Restoration Act: "In carrying out a covered project, the Secretary shall fully maintain, or  
56 contribute toward the restoration of the structure and composition of old growth stands  
57 according to the pre-fire suppression old growth conditions"<sup>1</sup>. One measure of pre-fire  
58 suppression conditions for many western forests is to reconstruct stand conditions from  
59 the mid to late 19<sup>th</sup> century, a period which had an active fire regime (Fulé et al. 1997;  
60 Taylor 2004, Landis and Bailey 2005). Current efforts to mimic pre-fire suppression  
61 forest conditions in California's Sierra Nevada, however, are difficult to assess because  
62 most information on 19<sup>th</sup> century forest conditions is limited to narratives (Muir 1911;  
63 LeConte [1875] 1930), photographic comparisons (Gruell 2001) or early but limited  
64 forest surveys (Fitch 1900; Lieberg 1902; Moore 1913, Stephens and Elliot-Fisk 1998,  
65 Stephens 2000).

66 While many methods of Sierran forest restoration are possible, Stephenson (1999)  
67 suggested they can generally be grouped into two approaches: *structural* restoration  
68 which emphasizes first restoring historic stand structure and composition through  
69 mechanical thinning, and *functional* restoration which prioritizes restoring ecological

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<sup>1</sup> <http://agriculture.senate.gov/forest/forhxadtsec.pdf>

70 processes such as fire. Some studies have suggested Sierran forests cannot be restored  
71 without first thinning the forest to reintroduce a clustered age cohort structure  
72 (Bonnicksen and Stone 1981; 1982). Others have suggested that prescribed fire can  
73 accomplish most stand reconstruction without first thinning the forest (Harvey et al.  
74 1980; Stephenson et al. 1991). When thinning is used, treatments have been  
75 controversial because prescriptions often propose thinning some intermediate ( $> 50$  cm  
76 diameter at breast height [dbh]) or large ( $> 75$  cm dbh) trees both to restore stand  
77 structure and to provide enough revenue to pay for treatments. In spite of these  
78 controversies, there has been little research in the Sierra Nevada on the effects of burning  
79 and different thinning intensities on structure, composition and spatial pattern of forests,  
80 and how these compare to historic conditions (Fig. 1).

81 In 1997 we established and mapped permanent plots to be treated with a  
82 combination of burning and thinning treatments in 2000 and 2001. We were interested in  
83 how widely used restoration treatments affect forest structure, composition and pattern,  
84 and how treatments compare to a reconstruction of forest conditions which had an active  
85 fire regime. Specifically we had 3 objectives: 1) how do current forest conditions differ  
86 from stand structure, composition and pattern in 1865 (the year of the last widespread fire  
87 at our study site); 2) how do fire and thinning treatments affect diameter distribution,  
88 species composition and spatial structure of mixed conifer; and 3) which treatment is  
89 most effective at moving current stand conditions toward reconstructed forest conditions  
90 produced by an active fire regime. We examined forest conditions intensively at the  
91 Teakettle Experimental Forest where we were able to apply a controlled field experiment

92 to replicated plots of old-growth, mixed-conifer forest, and sample ages and fire scars on  
93 stumps produced by the thinning treatments.

94

## 95 **Methods**

### 96 **Study area**

97 The study took place within the Teakettle Experimental Forest, a 1300 ha reserve  
98 of old growth on the north fork of the Kings River within the Sierra National Forest (Fig.  
99 2). The elevation ranges from 1900-2600 m, and annual precipitation of approximately  
100 125 cm falls almost entirely as snow between November and April (North et al. 2002).  
101 Teakettle's most common soil is mapped as a well-drained, mixed, frigid Dystric  
102 Xeropsamment, formed from decomposed granite, typical of many southern Sierra forests  
103 (Anonymous 1993).

104 Within Teakettle, forest type varies by elevation, grading from mixed conifer at  
105 lower elevations to red fir (*Abies magnifica*) on mid-slope, and to red fir and lodgepole  
106 pine (*Pinus contorta*) at higher elevations. Approximately 65% of Teakettle's forest is  
107 mixed conifer, which characteristically contains white fir (*Abies concolor*), red fir,  
108 California black oak (*Quercus kelloggii*), sugar pine (*Pinus lambertiana*), incense-cedar  
109 (*Calocedrus decurrens*), and Jeffrey pine (*Pinus jeffreyi*) (Rundel et al. 1988). As in  
110 most of California's mixed-conifer forests, white fir dominates stem density and basal  
111 area at Teakettle; however, sugar pine and Jeffrey pine are the largest diameter and tallest  
112 trees (North et al. 2002). An analysis of fire scars in Teakettle indicated that prior to  
113 European settlement, the fire return interval for the 200 ha experimental area was 11-18

114 years, and the last widespread fire (> 3 ha) occurred in 1865 (Fiegener 2002, North et al.  
115 2005a).

116 Our research focused on a 200 ha contiguous block of mixed conifer with similar  
117 soils (all mapped as the Cagwin series [Anonymous 1993]) derived from decomposed  
118 granite typical of the western slope of the Sierra Nevada. In this area, 18 permanent four-  
119 ha plots were established (Fig. 2) from prior data (North et al. 2002). Plot size (4 ha) was  
120 established using variogram analysis to estimate an area sufficiently large enough to  
121 include the range of variable forest conditions found in mixed conifer. Stand structure  
122 and the understory community were sampled on 600 quadrats on a 50 by 50 m systematic  
123 grid across the 200 ha block and quadrats were grouped with cluster analysis. The 4 ha  
124 plots were located within the 200 ha block so that each plot included the same  
125 proportional representation of the 4 vegetation conditions (closed canopy, shrub, gap and  
126 rock/shallow soil patches [North et al. 2002]) identified in the cluster analysis of the  
127 quadrats. An analysis of the forest structure and composition found no significant  
128 pretreatment differences between the 18 plots (North et al. 2002).

129

### 130 **Treatments**

131 The 18 plots were assigned to one of six treatments determined by the  
132 experimental design, a full factorial, crossing two levels of burning treatments  
133 (prescribed fire and no burn) and three levels of thinning treatments (none, understory  
134 and overstory) (Fig. 2). For some plots, management and operational constraints (e.g.,  
135 presence of a sensitive species such as the pine marten) limited which treatments could be  
136 applied, but after applying these constraints, treatments were allocated as randomly as

137 possible. The understory prescription followed guidelines in the California spotted owl  
138 (CASPO) report (Verner et al. 1992), which removes all trees between 25 and 76 cm (10  
139 and 30”) dbh while retaining at least 40% canopy cover. Although designed initially for  
140 minimizing impact to spotted owl habitat, the CASPO guidelines became the standard  
141 forest practice in the 1990s and are still widely used as a fuel reduction treatment  
142 (SNFPA 2004). The overstory prescription removed all trees > 25 cm dbh except for 22  
143 large diameter trees per hectare, which were left at regular spacing (approximately 20 m  
144 apart). The overstory thinning was widely practiced in Sierran forests before CASPO,  
145 and at Teakettle its marking resulted in a prescription of cutting dominant overstory trees  
146 up to 100 cm (40”) dbh. Increasing the diameter limit from 30 to 40” was widely debated  
147 in the late 1990s as a means of increasing sale revenues so that more stands could be  
148 treated for fuel reduction. The thinnings were applied in fall of 2000 (thin and burn  
149 plots) and early spring of 2001 (thin-only plots). Trees were limbed and topped where  
150 they fell and merchantable logs removed. The prescribed fire was applied by the Sierra  
151 National Forest following their standard operating procedures. Fuels from the thinning  
152 operations were left to dry for one year, and the prescribed fires were lit in fall of 2001 a  
153 week after the first substantial (2 cm) rainfall. All plots were burned within a one week  
154 period and the fire was extinguished by snow a week later.

155

#### 156 **Data collection and stand reconstruction**

157 Using a surveyor’s total station, all trees and snags ( $\geq 5$  cm dbh;  $N = 35,418$ ) in  
158 the eighteen 4 ha plots were measured, identified to species, mapped, and permanently  
159 tagged during the 1998-2000 field seasons before treatments were applied. Snags were

160 assigned a decay class (Cline et al. 1980) and a visual estimate of height recorded.  
161 Following treatments all plots were re-sampled and mapped during the 2002-2004 field  
162 seasons using the same protocols. All logs ( $\geq 30$  cm diameter) were tagged, mapped  
163 (four corners) and assigned a decay class (Maser and Trappe 1984). Only logs in decay  
164 classes I-IV were inventoried because field technicians could not reliably identify the  
165 dimensions of decay class 5 logs. Following treatments, logs were inventoried and  
166 mapped again, this time using diameter and azimuth, and identified to species.

167 To assess canopy cover, 402 hemispherical photographs were taken from  
168 regularly spaced sample points in each plot before and after treatments with a Nikon Cool  
169 Pix 950 digital camera and a Nikkor hemispherical FC-E8 0.21X fisheye converter (180°  
170 angle) lens. All photographs were taken in black and white at dawn or dusk with  
171 uniformly cloudless conditions using a level tripod, with the top of the photo oriented to  
172 true North.

173 To reconstruct historic stand structure to 1865 conditions, we generally followed  
174 methods used in Southwest ponderosa forests (Fulé et al. 1997, Mast et al. 1999, Moore  
175 et al. 2004) in which the size, species composition, and location of live trees during an  
176 active fire period are estimated from current live trees, snags and logs. We modified  
177 these reconstruction methods because of the mix of shade-tolerant and –intolerant species  
178 in mixed conifer, and added a measure of current growing space to refine species-specific  
179 estimates of past diameter.

180 First we took 539 ground-level cross section ‘cookies’ from post-treatment  
181 stumps in direct proportion to the species composition (by frequency) of stems within the  
182 stand. This provided a much higher sample size for the three shade-tolerant species,

183 white fir, red fir, and incense-cedar, which should have greater variability in annual basal  
184 area increment than the shade-intolerant pines (Oliver and Larson 1996). The 539 sample  
185 cookies were cut into cross sections and sanded with up to 400 grit sandpaper to improve  
186 visual identification of tree ring boundaries. Tree rings were measured from the last year  
187 of growth to the pith using a microscope and a Velmex “TA” tree ring system (Velmex  
188 Inc., Bloomfield, NY). Measurement resolution was 0.001 mm. Series were manually  
189 cross-dated using standard procedures (Stokes and Smiley 1968), and the annual basal  
190 area increment (BAI) for each tree was calculated for each year from 1865 to 2000. We  
191 subtracted the 1865 to 2000 radial increment to estimate ground-level inside bark  
192 diameter of each stem in 1865. Next, we used species-specific equations to estimate  
193 1865 outside bark diameter at breast height for each tree (Dolph 1981).

194         We calculated an approximation of local competition for each of the cookie-  
195 sampled trees using Thiessen polygons. The size and distribution of Thiessen polygons  
196 has been used to evaluate the impact of density, growing space and competition of  
197 neighboring plants on plant succession (Mithen et al. 1984, Kenkel et al. 1989). Using  
198 the stem map and ARC/INFO software, the area around each tree was bisected by a line  
199 equidistant between adjacent stem locations, and the lines are connected to form a  
200 polygon around each cookie-sampled tree location. The polygon’s area is an  
201 approximation of the potential growing space, in square meters, for an individual tree.  
202 Polygon size is a function of local stand density, with smaller areas indicative of dense,  
203 ‘dog hair’ conditions. Polygons were then weighted by dividing each polygon’s area by  
204 the basal area of the sample tree to take into account the greater growing space demands  
205 (i.e., light, water and nutrients) of larger trees. This approximation of growing space is

206 estimated from current conditions and therefore its utility is based on an assumption that  
207 reductions in BAI from fire-suppressed stem density increases will be correlated with  
208 present stand conditions.

209 For each species we built regression models to predict 1865 dbh from dbh in 2000  
210 (recorded before the tree was cut) and the weighted Theissen polygon size. Using the  
211 best-fit equations for each species, we then estimated 1865 diameters for all trees in the  
212 eighteen plots using the 72 ha pre-treatment stem map and the weighted Theissen  
213 polygon calculated for each tree.

214 In addition to the live-tree estimate, reconstruction estimates were made using the  
215 stem map of snags and logs. In mixed conifer, the year of death often cannot be  
216 determined using increment cores because many pieces have extensive heartwood and  
217 sapwood rot. To estimate when a snag died, we used the field rating of the decay class of  
218 each snag and applied published estimates for the transition time between decay classes  
219 for Sierran mixed-conifer species (Raphael and Morrison 1987; Morrison and Raphael  
220 1993) to estimate the decade in which a snag originated. Using the 539 cookies, we  
221 calculated mean BAI for each of the 5 principle species in 25 cm diameter classes. We  
222 estimated each snag's live 1865 dbh using the formula:

223 
$$1865 \text{ dbh} = 2000 \text{ dbh} - [(\text{midyear of death decade} - 1865) * (\text{BAI})] + \text{estimated}$$
  
224 bark thickness (if missing in 2000)

225 To estimate 1865 tree size from current logs, we used published estimates of log  
226 age for different decay classes (Kimmey 1955; Harmon et al. 1987) to estimate the  
227 decade during which a log originated. We then used time estimates for snag fall rates in  
228 unburned forest (Raphael and Morrison 1987) to estimate decade of tree death and then

229 applied the equation listed above to estimate dbh in 1865. This approach should be a  
230 conservative estimate of tree size because live trees may be wind toppled and directly  
231 become logs without going through a snag phase. Field observations, the rarity of tip-up  
232 mounds, and the lack of a consistent azimuth in log orientations (Innes et al. in press),  
233 however, suggest most trees at Teakettle go through a snag phase rather than directly  
234 becoming logs due to wind events.

235         While there are several limitations to these reconstruction methods, the most  
236 significant is our estimate of the density and location of small trees. Our tally of logs and  
237 snags in 1998-2000 would fail to detect small diameter trees which died after 1865 and  
238 completely decayed before our survey. Using estimates of log decay rates (Harmon et  
239 al.1987) and snag fall rates (Morrison and Raphael 1993), we can roughly estimate that  
240 small diameter ( $\leq 25$  cm diameter) white fir, the species with the fastest decomposition  
241 rate, that died in 1940 or later would still have at least 20% of their bole mass in 2000 and  
242 be detected in our log survey (decay classes 1-4). We have no way of estimating how  
243 many small trees died before 1940 or how many are still alive. An earlier demography  
244 study at Teakettle did find many small-diameter white firs from the 1880s still alive even  
245 in high-density thickets (North et al. 2005a). Our survey is much more likely to detect  
246 larger diameter trees and other species which have slower decay rates. This bias means  
247 our 1865 reconstruction underestimates small tree density and small scale clustering  
248 (because small stems are usually clumped). This bias is less likely to significantly affect  
249 our estimates of basal area, volume, density of large trees or large scale spatial patterns.

250

251 **Analyses**

252 To develop species-specific models for estimating 1865 diameter from 2000 dbh  
253 we assessed whether BAI and weighted Thiessen polygon values were normally  
254 distributed using the Shapiro-Wilks test. Values for the three shade-tolerant species  
255 (white and red fir, and incense-cedar) and all weighted Thiessen polygons values were  
256 not normally distributed and therefore were log transformed.

257 To evaluate different predictive models using combinations of BAI, weighted  
258 Thiessen polygon size, and interaction terms, we used Akaike's Information Criteria  
259 (AIC) (Burnham and Anderson 2002). All terms were added to the model, and then  
260 terms were dropped if their  $C_p$  statistic (the likelihood version of AIC in S-PLUS) was  
261 lower than the  $C_p$  statistic for the full model.

262 Current canopy cover was estimated using hemispherical photographs analyzed  
263 with Gap Light Analyzer 2.0 (Frazer et al. 2000). We compared measures of stand  
264 structure (basal area, density, quadratic mean diameter, volume and species composition  
265 percentages) between all treatments and the 1865 reconstruction using ANOVA and a  
266 Tukey's post-hoc test. All analyses were completed using S-Plus statistical software (S-  
267 Plus 2001).

268 Tests of spatial distribution were made using Spatial Point Pattern Analysis  
269 software (Haase 1995) and univariate Ripley's K analyses. Ripley's K compares  
270 distances between all location points in the same plane (Ripley 1979; Diggle 1983) using  
271 the reduced second moment measure or K function to examine spatial associations. We  
272 calculated 99% confidence intervals using 100 Monte Carlo simulations. We examined  
273 the distribution of all trees in the 18 plots in estimated 1865 conditions, and before and  
274 after treatments.

275

## 276 **Results**

277           The most parsimonious models for estimating 1865 dbh for all species except  
278 Jeffrey pine included two terms, 2000 dbh and weighted Thiessen polygon size. Multiple  
279 adjusted  $R^2$  values were 0.69 for white fir, 0.70 for red fir, 0.63 for incense-cedar and  
280 0.73 for sugar pine. The best model for Jeffrey pine used only 2000 dbh and had an  
281 adjusted  $R^2$  of 0.83.

282           Pre-treatment forest conditions at Teakettle significantly differed from the active  
283 fire forest reconstruction in stem density, quadratic mean diameter, and species  
284 composition (Table 1). Although the 1865 forest had a much lower stem density than  
285 modern conditions (67 vs. 469 trees/ha), there was no significant difference between the  
286 two conditions in basal area (51.5 vs. 56.4  $m^2/ha$ ) or volume (393.2 vs. 434.6  $m^3/ha$ ),  
287 because the fewer trees were larger in size (49.5 vs. 19.6 cm). A significant shift in forest  
288 composition has occurred with pretreatment conditions having 84% and 14% shade  
289 tolerants and intolerants, compared to 51% and 49%, respectively, in 1865. Most of that  
290 change was due to the significant increase in the percentage of white fir and decrease in  
291 Jeffrey and sugar pine percentages.

292           All of the thinning treatments significantly reduced basal area below current and  
293 historic conditions, however all except the overstory thin and burn (93.6 stems/ha) still  
294 retained significantly more stems than were present in 1865 (Table 1). Canopy cover was  
295 reduced directly in proportion to thinning intensity with no significant differences  
296 between burn and no burn plots within the same thinning intensity. None of the  
297 treatments produced a significantly different quadratic mean diameter from one another

298 (21.9-28.9 cm); however, all were significantly lower than historic conditions (49.5 cm).  
299 All treatments reduced stem volume, but only the two overstory thinning treatments  
300 (200.5 and 141.8 m<sup>3</sup>/ha) significantly reduced volume below historic (393.2 m<sup>3</sup>/ha) or  
301 current conditions (434.6 m<sup>3</sup>/ha).

302 Stand composition was only marginally affected by treatment and still  
303 significantly differed from historic conditions. None of the treatments significantly  
304 reduced the percent of white fir (57.7-67.6%) which was almost double the historic value  
305 (33.7%). Both burning and thinning treatments (20.8 and 22.4%) significantly increased  
306 the percentage of incense-cedar compared to other treatments (9.5-15.8%), current  
307 (13.4%) and historic (14.5%) conditions. There was no significant difference in either  
308 sugar and Jeffrey pine percentages between treatments, but all treatments had about 1/3  
309 the pine percentage of historic conditions. Burning increased small stem mortality and  
310 produced significantly higher snag densities (92.4-123.4 stems/ha), but did not impact  
311 species composition, basal area or canopy cover substantially.

312 The most significant difference in diameter distribution was between historic  
313 conditions and the current forest pre- and post-treatment (Fig. 3). In 1865, the diameter  
314 distribution was almost flat with nearly equal stem numbers in each 25 cm dbh class. In  
315 contrast, all of the treatments have very high stem numbers in the small diameter classes  
316 and much fewer large size trees. All treatments do not significantly change the reverse-J  
317 shaped distribution present in the pretreatment forest. The number of 50-75 cm stems  
318 was reduced in all thinning treatments (4.2-8.9 stems/ha) below historic levels (11.2  
319 stems/ha). In size classes greater than 75 cm, overstory thinning significantly reduced the  
320 number of large trees below their historic density. Historically there were more trees in

321 the large size classes (>100 cm dbh) than in current conditions or following any of the  
322 treatments, particularly for the largest size class (>150 cm dbh).

323 Tree spatial patterns have significantly changed from 1865 to current conditions  
324 with the most noticeable change being the sparse, low-density distribution in 1865 (Fig.  
325 4a) compared to pretreatment conditions (Fig. 4b). The reconstruction shows trees were  
326 slightly clustered up to 60 m (Fig. 4a) compared with pretreatment stem distribution  
327 where trees were strongly clustered. At this scale, the clustering effect is strongly  
328 influenced by the high number of small trees regenerating in existing tree groups (North  
329 et al. 2004). Burn treatments (Fig. 4c, 4e, and 4g) killed more small trees but there was  
330 only a small reduction in how strongly trees were clustered at small to intermediate  
331 distances (0-60 m) over similar treatments without burning. Thinning-only treatments  
332 (Fig. 4d and 4f), which did not remove trees under 25 cm dbh, did little to reduce  
333 clustering over the 0 to 60 m scale.

334 At larger scales (> 60 m) the reconstruction shows that the 1865 stem distribution  
335 was random (Fig. 4a). Only the burn and understory thinning treatment (Fig. 4e)  
336 produced a similar distribution at this scale. Burning alone (Fig. 4c) slightly reduces the  
337 degree of clustering at large scales from pre-treatment condition. The understory  
338 thinning (Fig. 4d) reduces clustering at intermediate scales (40-60 m) but did not restore a  
339 random distribution at larger scales. As expected the overstory thin and burn treatment  
340 (Fig. 4g), which left 22 large trees per hectare evenly spaced, significantly made stands  
341 regularly distributed at large scales. The pattern, however, was not present in the  
342 overstory thin-only treatment (Fig. 4f) because many small trees (<25 cm dbh) were left  
343 producing a clustered distribution at larger scales.

344

345 **Discussion**

346           We compared an 1865 reconstruction to current and treated stands to assess  
347 whether treatments approximate forest conditions produced by an active fire regime. This  
348 comparison, however, is not an endorsement of regressing forests to a pre-European  
349 condition. Efforts to recapture a historic condition are probably misguided as elimination  
350 of Native American ignitions (Anderson and Moratto 1996), changes in grazing intensity  
351 (Douglass and Bilbao 1975; Rowley 1985), and climate change (Millar and Wolfenden  
352 1999; Pierce et al. 2004) have substantially changed factors that influenced forest  
353 composition and structure. A goal of effective restoration is re-establishing conditions  
354 characteristic of the evolutionary environment of an ecosystem (Falk 1990; Society for  
355 Ecological Restoration 1993). Many studies have shown that frequent, low-intensity fire  
356 has been a key process shaping Sierran mixed conifer (Agee et al. 1978; Vankat and  
357 Major 1978; Kilgore and Taylor 1979; Parson and DeBenedetti 1979). Our comparison  
358 with 1865 conditions is intended as a reference point for mixed-conifer conditions  
359 produced by an active fire regime and not as a strict prescription for contemporary  
360 restoration (Falk 1990; White and Walker 1997).

361           Our analysis supports the concept that active fire regime stands were low-density,  
362 with a high proportion of large size trees, and a substantially higher proportion of shade-  
363 intolerant pine species. Lieberg (1902) describes central Sierra mixed-conifer forests in  
364 which densities were low and most were stems > 62 cm (25") dbh. Sudworth (1900a;  
365 1900b) using data from a limited number of mixed-conifer plots shows a higher average  
366 density (92 stems/ha) than we found (Table 1), but a much higher number of very large

367 trees. A large scale (>2300 plots) 1930's survey of Sierran forests (Bouldin 1999) found  
368 much higher mixed-conifer stem densities (140-218 stems/ha) than we did, but this was  
369 already several decades after Sierran fire regimes had changed. Estimates of species  
370 composition vary by location (McKelvey and Johnson 1992) with shade-intolerant pine  
371 making up 30-50% of the stems (Moore 1913; Sudworth 1900a; 1900b; Fitch 1900) in  
372 early surveys. These historical data sets, however, should be treated with caution because  
373 there is little information on sampling protocols or how plots were located. Bouldin  
374 (1999), for example, has suggested that Sudworth's data is significantly biased from  
375 locating plots in exemplary groves of large trees.

376         Our estimate of 1865 forest conditions should be viewed with caution because it  
377 is limited by problems common to reconstruction analyses and the constraints of our field  
378 sampling. White and Walker (1997) suggest that all reconstructions be explicit about  
379 their spatial and temporal limits, and potential biases in their reconstruction methods.  
380 Our analysis is focused on one old-growth area where we have the intensive data needed  
381 to reconstruct stand conditions on 72 ha back to the last fire. Any effort to reconstruct  
382 earlier conditions would be difficult because frequent fires would have consumed woody  
383 material. Our reconstruction methods are also limited by imperfect predictive models of  
384 past diameter, broad estimates of death date from decay class, and better records for  
385 species, such as incense-cedar, with slower decay rates. Our estimates of the density and  
386 spatial location of small trees are less accurate than our large tree estimates because our  
387 1998-2000 survey would miss small trees that died within a few decades of Teakettle's  
388 last fire in 1865. Our estimates of 1865 stand conditions, however, are similar to a  
389 reconstruction of 19<sup>th</sup> century stands in the Lake Tahoe area, which found comparable

390 stem densities and stands dominated by large pines (Taylor 2004). We know of one  
391 contemporary mixed-conifer area, Aspen Valley in Yosemite National Park, with a fairly  
392 active fire regime (3 understory burns in the last 40 years) that has never been  
393 mechanically thinned. Aspen Valley has a higher density than Teakettle's reconstruction  
394 (102 vs. 69 stems/ha), and a higher percentage of pine (64%), but a similar low density of  
395 small size trees and a nearly flat diameter distribution curve (Monica Buehler, Yosemite  
396 N.P. Fire Ecologist, unpublished data). We believe Teakettle's 1865 forest conditions are  
397 within the range of historical forest surveys and other reconstructions. Our focus with  
398 this research was to compare stand conditions produced by different restoration  
399 treatments with those produced by an active fire regime in old-growth mixed conifer.

400         Our reconstruction suggests that effective treatments should drastically reduce  
401 small tree (< 50 cm dbh) densities, retain some intermediate and all large trees,  
402 significantly decrease the percentage of white fir and reduce stem clustering. None of the  
403 treatments in our experiment achieved all of these objectives, but the understory thinning  
404 and prescribed burn was more effective than the other treatments.

405         All treatments had about 10 times more 5-25 cm dbh trees than our rough estimate  
406 of this size class in 1865. Our methods underestimate small tree density but even with a  
407 tripling of our estimate, treatments would still have more than 3 times too many small  
408 trees. Mechanical thinning prescriptions did not cut any tree less than 25 cm dbh (10")  
409 based on the assumption that logging damage and prescribed fire would substantially thin  
410 this size class (Mark Smith, Sierra National Forest, personal communication). Logging  
411 damage and prescribed fire did reduce the number of stems by 15-65% in the 5-25 cm  
412 size class, but even the most intense treatment, overstory thinning and prescribed fire still

413 averaged 87 small stems/ha compared to roughly 9 stems/ha in 1865. These small trees  
414 are usually unmerchantable, so their reduction in restoration treatments often depends on  
415 whether funds are available for a prescribed burn or for their removal with a  
416 supplemental service contract. Repeated prescribed burns would also help reduce this  
417 size class toward historic conditions.

418 All thinning and thinning/burning treatments reduced trees to near historic levels  
419 in the 25-50 cm class, but removed too many trees in the 50-75 cm class (Fig. 3). In the  
420 Sierra Nevada some of the controversy over restoration treatments has focused on the 50-  
421 75 cm size class because the trees have enough commercial value to help pay for thinning  
422 and prescribed fire treatments, but they also provide the next generation of large, old  
423 trees. At Teakettle, the reconstruction suggests this size class had approximately 11  
424 trees/ha while thinning treatments significantly reduced this size class's density (4-9  
425 trees/ha) below historic levels (Fig. 3). Trees remain in this size class even in the  
426 understory prescription (removal of all trees between 25 and 75 cm) because of errors in  
427 marking, wildlife 'leave trees' and leaving trees that are hazardous to fall.

428 Current Sierran thinning prescriptions (i.e., the understory treatment), leave all  
429 trees  $\geq 76$  cm (30") which in our experiment left comparable stem densities in the 75-99  
430 cm class to 1865 conditions. Overstory thinning (removing trees up to 100 cm or 40"  
431 dbh) significantly reduced the density of large trees ( $\geq 76$  cm dbh) below 1865 levels and  
432 drastically reduced stand basal area and volume, producing a stand structure that  
433 substantially departed from historic conditions. For trees  $\geq 100$  cm, 1865 had a higher  
434 density than any of the treatments or even current unharvested, old-growth conditions.  
435 Smith et al. (2005) suggested this reduction in large trees in current old growth may be

436 due to recent mortality from pest and pathogens during extended droughts. Some studies  
437 (Ferrell et al. 1994; Ferrell 1996) suggest that modern increases in stem density increase  
438 moisture stress, such that during droughts tree vigor declines and mortality increases  
439 from pests and pathogens. This implies that even in stands of unmanaged old growth,  
440 current large tree density may be lower than was present under an active fire regime.

441 Restoration thinning prescriptions sometimes rely on principles of uneven-aged  
442 silviculture (Smith 1986), which suggest thinning to a negative exponential or reverse-J  
443 shaped diameter distribution for diversifying structure. O'Hara (2001; O'Hara and Geof  
444 2004), however, has pointed out seral development and local disturbance patterns can  
445 produce a wide variety of diameter distributions in natural stands. Although the current  
446 diameter distribution at Teakettle and in other old-growth stands (Ansley and Battles  
447 1998; Minnich et al. 1995) has a reverse-J shape, Bouldin (1999) found a wide variety of  
448 diameter distributions in stands in the 1930s. The 1865 reconstruction suggests that  
449 under an active fire regime, Teakettle may have had a much flatter diameter distribution.  
450 Our reconstruction methods underestimate small tree densities and lower the left side of  
451 the diameter distribution below what it likely was in 1865. We believe, however, it's  
452 unlikely that we've underestimated this size class's density by ten fold, the increase  
453 needed to produce a reverse-J distribution. An earlier study of Teakettle's tree  
454 demography found frequent episodes of mortality and establishment following fires and  
455 wet climate years (North et al. 2005a). This demographic pattern could produce a fairly  
456 flat diameter distribution if diameter was loosely correlated with age in low density open  
457 stands produced by frequent fire.

458 Species composition has substantially shifted from almost a 50/50 split between  
459 shade-tolerant (fir and cedar) and intolerant (pine) species in 1865 to 84% and 14%,  
460 respectively, in 2000 in Teakettle's untreated forest. Treatments did not fundamentally  
461 change this composition. The composition of the thinned trees was similar to current  
462 stand composition because the thinning prescription was strictly based on diameter.  
463 White fir, which is considered fire sensitive, should suffer higher mortality than pine in a  
464 prescribed burn. However, in our study and in others (Hanson and North 2006), many  
465 white fir were large enough to be fire resistant to all but the hottest spot burns. Similar to  
466 Van Mantgem et al. (2004), we had many large sugar pines die even under moderate burn  
467 conditions. These patterns suggest more field manipulation studies are needed to assess  
468 optimal fire frequency and intensity for increasing pine percentage in treated forest  
469 stands.

470 The prescribed fire without thinning treatment had only a moderate effect on  
471 stand conditions in our experiment probably because it was a low-intensity late fall burn.  
472 As is typical in the Sierra Nevada, Teakettle's prescribed fire was lit 'off-season' in late  
473 October for easier containment and when air quality conditions allow more burning. Fire  
474 may not do as much 'work' in this condition of lower temperatures and higher humidity  
475 without the addition of thinning slash to fuel fire intensity and increase burn coverage.  
476 Prescribed fire may need to be repeatedly applied to help move stand structure toward  
477 historic conditions. Stem density was significantly lower and snag density higher in both  
478 thinning and burn treatments where the fire burned hotter than in the other treatments. In  
479 these late fall burns, the importance of thinning before prescribed burning may be that it  
480 increases the extent and intensity of the fire.

481 Small-scale stem patterns appear to have always been clumped but current and  
482 treated forests are significantly more clustered than in 1865. Limitations in our  
483 reconstruction methods will produce underestimates of small scale clumping; however  
484 we believe this bias is unlikely to make up the pronounced difference between historic  
485 and modern conditions. Reducing small scale density can be an important measure of  
486 restoration because it contributes to fuel loading (Stephens and Moghaddas 2005),  
487 moisture stress (Feeney et al. 1998), and low light understory conditions that reduce plant  
488 diversity (North et al. 2005b) and shade-intolerant regeneration (Gray et al. 2005).  
489 Thinning treatments in our experiment did little to reduce this clustering because there  
490 was limited incidental mortality in the 5-25 cm size class produced by mechanical  
491 removal of larger trees. Prescribed fire did reduce small scale clustering particularly with  
492 higher burn intensities in the thinned plots, but many small trees still survived. Effective  
493 restoration may require more aggressive removal of stems in this size class, reducing  
494 density toward the 10 stems/ha suggested in the reconstruction.

495 Our study also suggests that restoration treatments need to reduce larger scale  
496 (>60 cm) clustering and produce a more random distribution of stems at the stand level.  
497 Comparing historic and current conditions in three forest communities (Jeffrey pine-  
498 white fir, red fir-western white pine, and lodgepole pine) in the Lake Tahoe Basin, Taylor  
499 (2004) also recommended that restoration treatments should reduce clustering and  
500 produce a more random distribution. Teakettle's pretreated forest was strongly clustered  
501 and most treatments failed to achieve a random distribution at large scales. Understory  
502 thinning and burning was the most effective at approximating historic spatial structure

503 because it retained all large trees, reduced stem density, and provided slash which  
504 increased fire intensity and mortality of small trees.

505 In our experiment one of the main reasons treatments did not restore active-fire  
506 stand conditions was because prescriptions thinned stands based on a strict diameter limit  
507 applied to all species. Many Sierran mixed-conifer stands have a small percentage of old  
508 shade-intolerants and in these cases few if any ponderosa, Jeffrey and sugar pine need to  
509 be thinned. Strict diameter limits also left too many small trees and over harvested  
510 intermediate-sized trees reducing future replacements for dying large trees. At Teakettle,  
511 2-5 large trees/ha ( $> 75$  cm dbh) died following understory thinning and prescribed  
512 burning treatments. This loss combined with the current deficit of large trees ( $> 150$  cm)  
513 suggests that more intermediate size trees may need to be retained to provide for large  
514 tree development. Understory thinning combined with prescribed fire was most effective  
515 at moving stand conditions toward those produced by an active fire regime, but new  
516 thinning prescriptions may be needed that vary by species and that retain more  
517 intermediate-sized trees to provide for future large tree recruitment.

518

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733 White, P.S. and Walker, J.L. 1997. Approximating nature's variation: Selecting and  
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736 Table 1. Stand structure and composition in 1865 (reconstructed), pretreatment, and for 5 treatments at the Teakettle Experimental  
 737 Forest. Species composition percentages were calculated using stem frequency. Other species and snags could not be estimated for  
 738 the 1865 reconstruction. Canopy cover was calculated from 67 hemispherical photographs taken in each treatment. Values within the  
 739 same row with different superscripts are significantly different ( $p < 0.05$ , Tukey's post-hoc ANOVA analysis). Species composition  
 740 percentages for the 1865 reconstruction were calculated using all trees but only those logs and snags which could be identified to  
 741 species.

Stand attribute	1865	Pretreatment	Understory thin only	Overstory thin only	Burn only	Burn/Under -story thin	Burn/Over- story thin
Basal area (m <sup>2</sup> /ha)	51.5 <sup>a</sup>	56.4 <sup>a</sup>	41.2 <sup>b</sup>	22.7 <sup>c</sup>	53.7 <sup>a</sup>	37.5 <sup>b</sup>	17.2 <sup>c</sup>
Total Density (stems/ha)	67 <sup>a</sup>	469 <sup>b</sup>	239.5 <sup>c</sup>	150.3 <sup>d</sup>	353.8 <sup>e</sup>	143.4 <sup>d</sup>	93.6 <sup>a</sup>
Cut (stems/ha)	NA	0	170.8	192.3	0	162.8	198.9
B.A. removed (m <sup>2</sup> /ha)	NA	0	20.2	33.9	0	21.3	37.0
Canopy cover (%)	Unk	80.7 <sup>a</sup>	72.8 <sup>b</sup>	63.4 <sup>c</sup>	80.5 <sup>a</sup>	70.9 <sup>b</sup>	60.2 <sup>c</sup>
Quadratic mean dbh (cm)	49.5 <sup>a</sup>	19.6 <sup>b</sup>	23.4 <sup>b</sup>	21.9 <sup>b</sup>	22.0 <sup>b</sup>	28.9 <sup>b</sup>	24.2 <sup>b</sup>

Volume (m <sup>3</sup> /ha)	393.2 <sup>a</sup>	434.6 <sup>a</sup>	397.7 <sup>a</sup>	200.5 <sup>b</sup>	423.0 <sup>a</sup>	372 <sup>a</sup>	141.8 <sup>c</sup>
Shade tolerant:							
<i>Abies concolor</i>	33.7% <sup>a</sup>	67.6% <sup>b</sup>	67.2% <sup>b</sup>	66.3% <sup>b</sup>	67.6% <sup>b</sup>	64.1% <sup>b</sup>	57.7% <sup>b</sup>
<i>A. magnifica</i>	2.9% <sup>a</sup>	3.0% <sup>a</sup>	4.7% <sup>a</sup>	1.9% <sup>a</sup>	2.5% <sup>a</sup>	1.2% <sup>a</sup>	1.0% <sup>a</sup>
<i>Calocedrus decurrens</i>	14.5% <sup>a</sup>	13.4% <sup>a</sup>	11.8% <sup>a</sup>	9.5% <sup>a</sup>	15.8% <sup>a</sup>	20.8% <sup>b</sup>	22.4% <sup>b</sup>
Shade intolerant:							
<i>Pinus Jeffreyi</i>	22.1% <sup>a</sup>	6.2% <sup>b</sup>	3.9% <sup>b</sup>	8.1% <sup>b</sup>	3.6% <sup>b</sup>	7.4% <sup>b</sup>	7.6% <sup>b</sup>
<i>Pinus lambertiana</i>	26.8% <sup>a</sup>	7.9% <sup>b</sup>	9.8% <sup>b</sup>	12.1% <sup>b</sup>	9.2% <sup>b</sup>	5.1% <sup>b</sup>	8.8% <sup>b</sup>
Other*	Unk.	1.9% <sup>a</sup>	2.6% <sup>a</sup>	2.1% <sup>a</sup>	1.3% <sup>a</sup>	1.4% <sup>a</sup>	2.5% <sup>a</sup>
Snag (stems/ha)	Unk.	39.0 <sup>a</sup>	37.8 <sup>a</sup>	32.3 <sup>a</sup>	92.4 <sup>b</sup>	120.3 <sup>b</sup>	123.4 <sup>b</sup>

742 \* Other species were the following hardwoods: California black oak (*Quercus kelloggii*), interior live oak (*Q. wislizenii*), canyon live  
743 oak (*Q. chrysolepis*), bittercherry (*Prunus emarginata*), and willow (*Salix spp.*).

744 **Figure captions**

745 Fig. 1: Forest conditions in mixed conifer in a) 1900 (Tuolumne county), b) Teakettle  
746 pre-treatment (2000), and c) Teakettle after an understory thin and burn treatment (2003).

747

748 Fig. 2: Location and shape (30 m. digital elevation model) of the Teakettle Experimental  
749 Forest. The table shows the treatments in the full-factorial design and the topographic  
750 map indicates each 4 ha plot location, treatment (from the table's abbreviations) and  
751 replicate number (1-3).

752

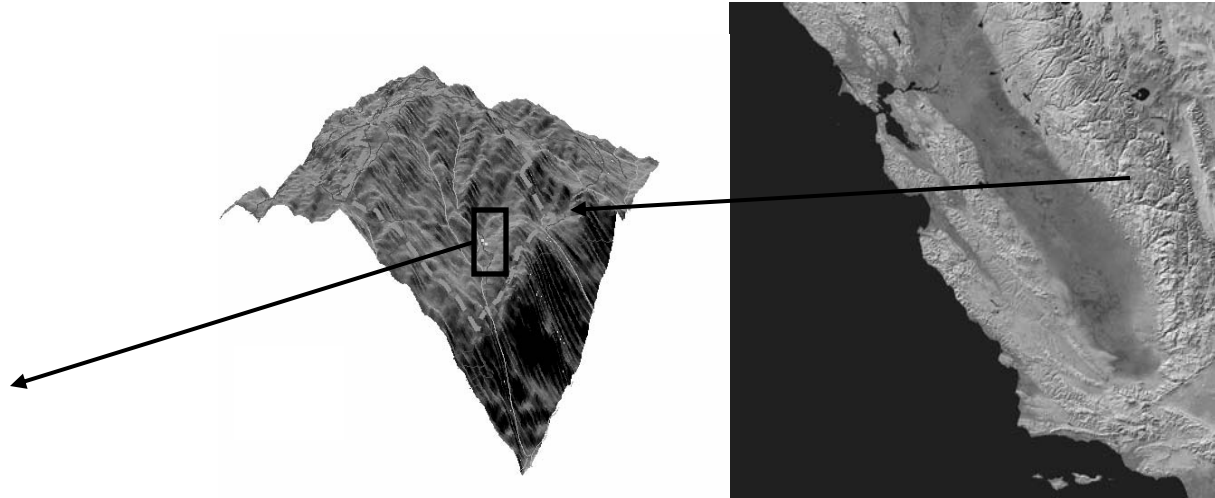
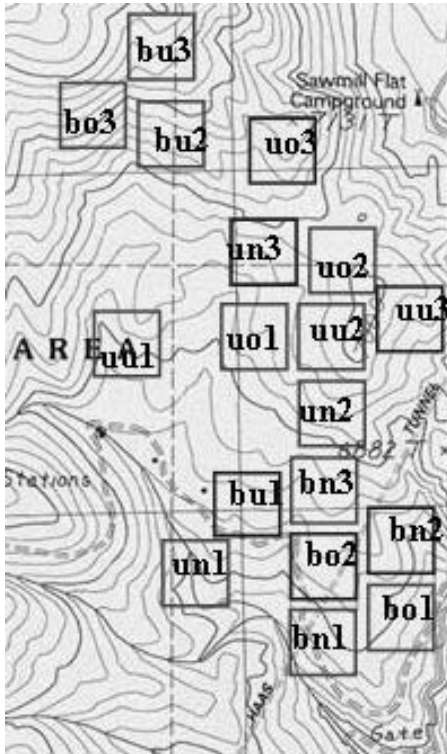
753 Fig. 3: Density of live trees (stems per hectare) in 7 size classes for 7 conditions in the  
754 Teakettle Experiment. Note that the smallest size class is less than a 25 cm range  
755 because only trees  $\geq 5$  cm were tallied.

756

757 Fig. 4: Stem distribution and spatial analysis of all live trees ( $\geq 5$  cm dbh) for a  
758 representative plot in each of 7 conditions. Conditions are; a) 1865 reconstruction, b)  
759 pretreatment, c) burn only, d) understory thin only, e) burn and understory thin, f)  
760 overstory thin, and g) burn and overstory thin. Circle size on the stem map is  
761 proportional to diameter and species are color coded where abco is white fir, abma is red  
762 fir, cade is incense-cedar, pije is Jeffrey pine, pila is sugar pine and unk is unknown. The  
763 graph for each condition shows the spatial distribution calculated using univariate  
764 Ripley's K. The stem pattern is the solid line and 99% confidence intervals are the two  
765 dashed lines. The stem pattern is considered to be significantly aggregated for those  
766 distances (m along the x axis) over which the solid line is above the upper dashed line,

767 and regularly distributed for those distances over which the solid line is below the lower  
768 dashed line. Stem map and Ripley's K analysis for figures 4a, 4b, and 4e are for the  
769 same 4 ha plot (BU1) in years 1865, 2000, and 2003 respectively.





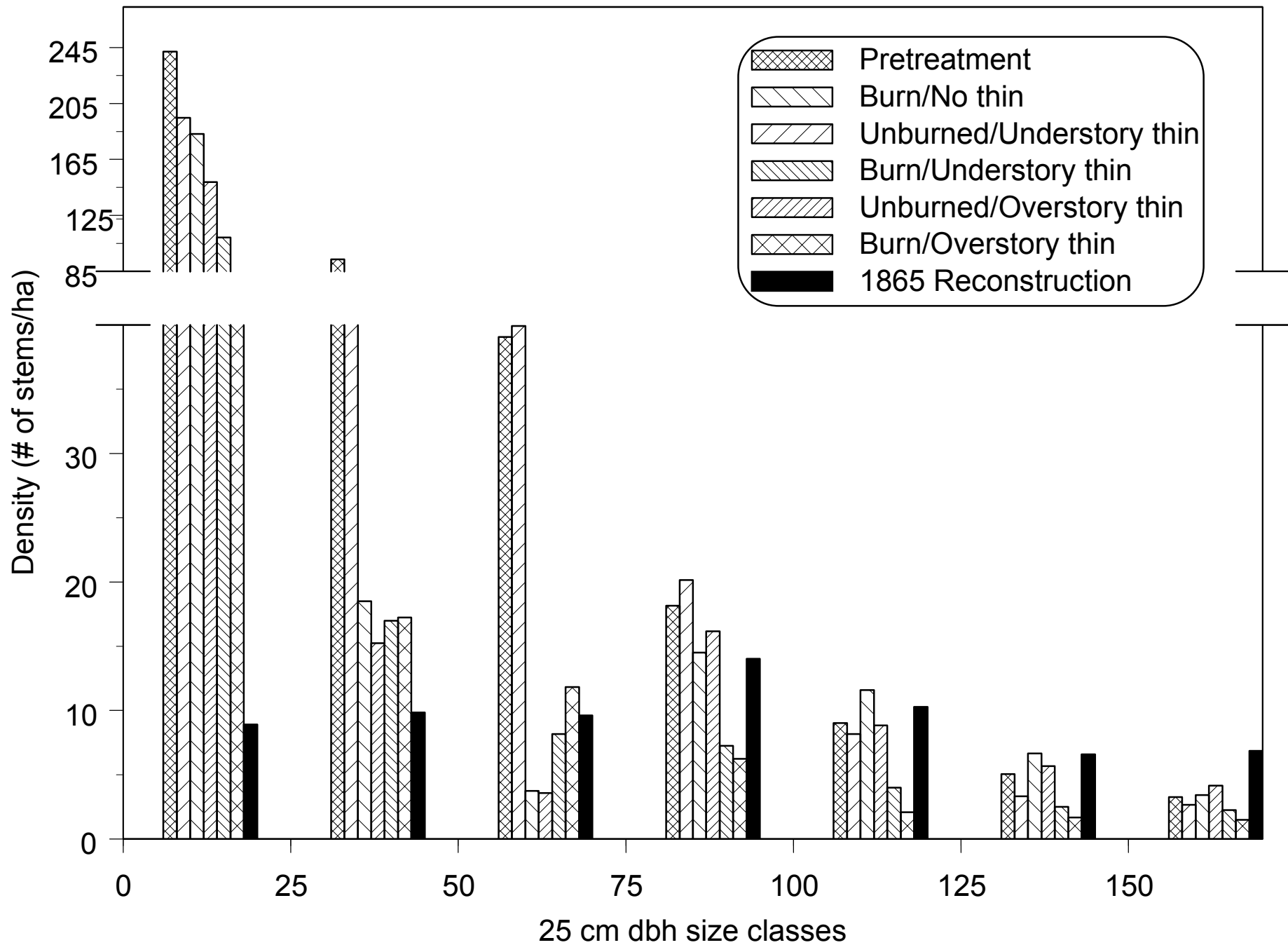
Thinning Level:

None

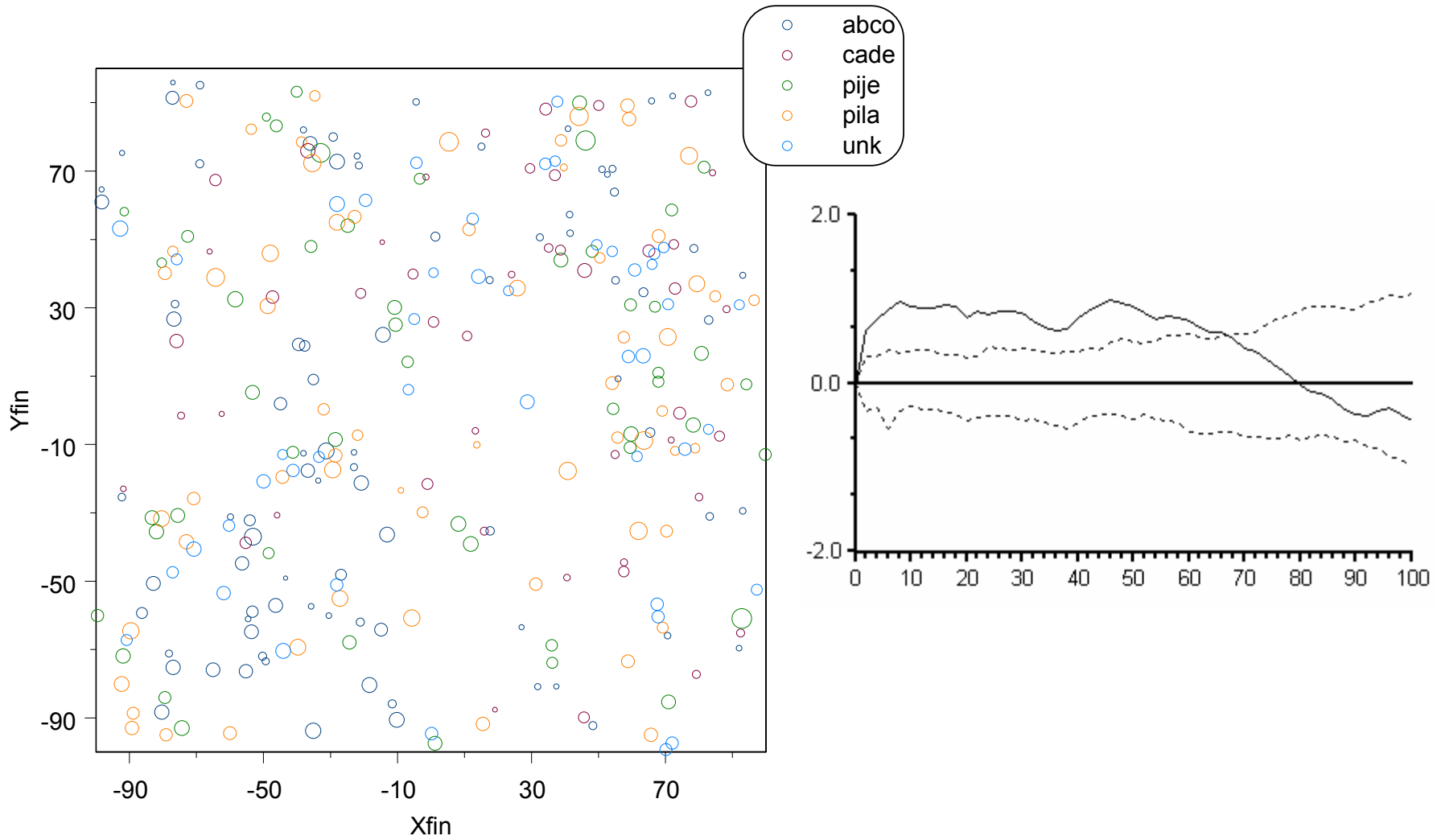
Understory thin  
( $25\text{ cm} < \text{thin} < 76\text{ cm}$ )

Overstory thin  
( $25\text{ cm} < \text{thin} \ \& \ \text{leave } 22 \text{ large t/ha}$ )

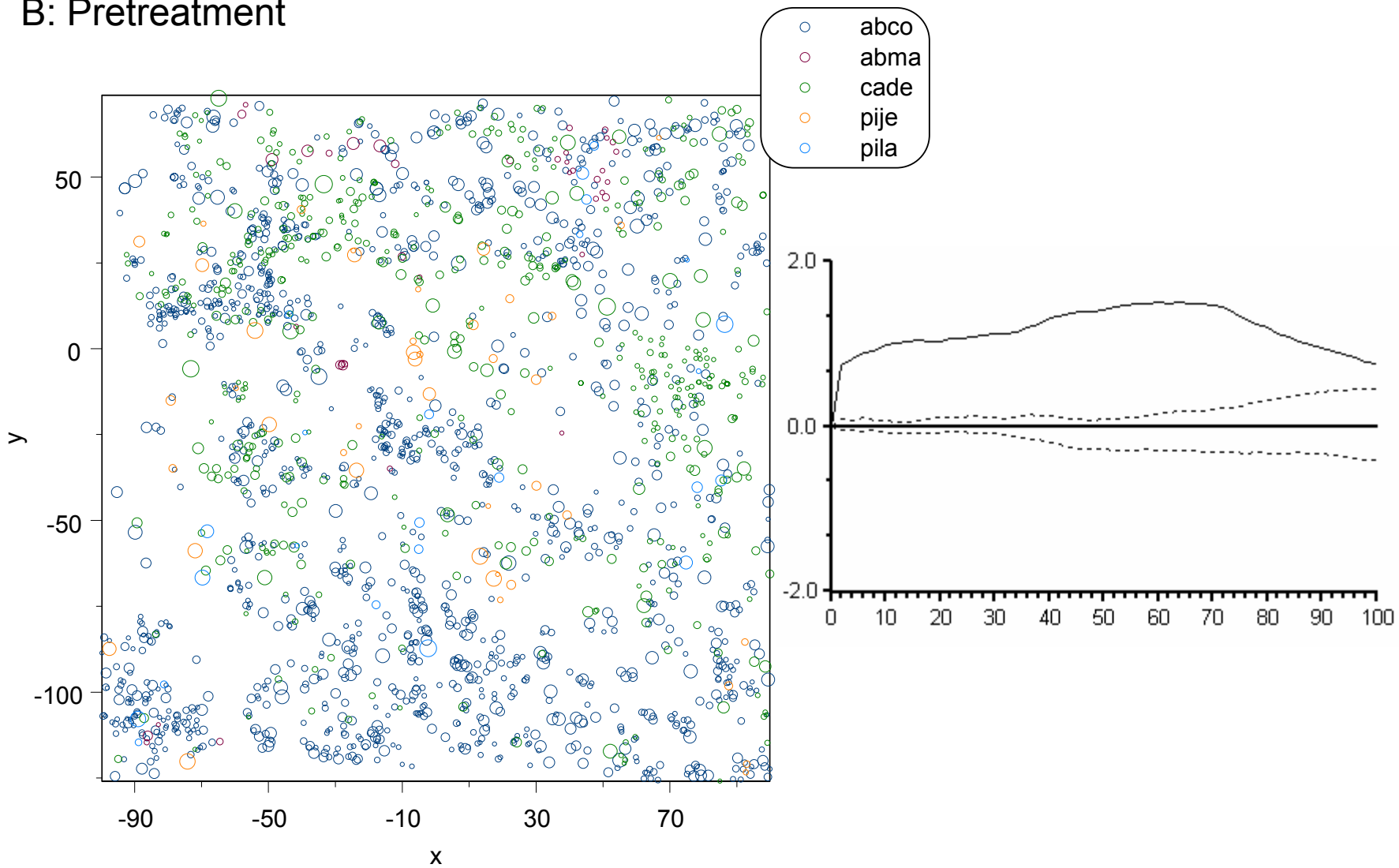
	Unburned	Burn
None	Control (UN)	Burn Only (BN)
Understory thin	Unburned/Thin from below (UU)	Burn/Thin from below (BU)
Overstory thin	Unburned/Overstory thin (UO)	Burn/Overstory thin (BO)



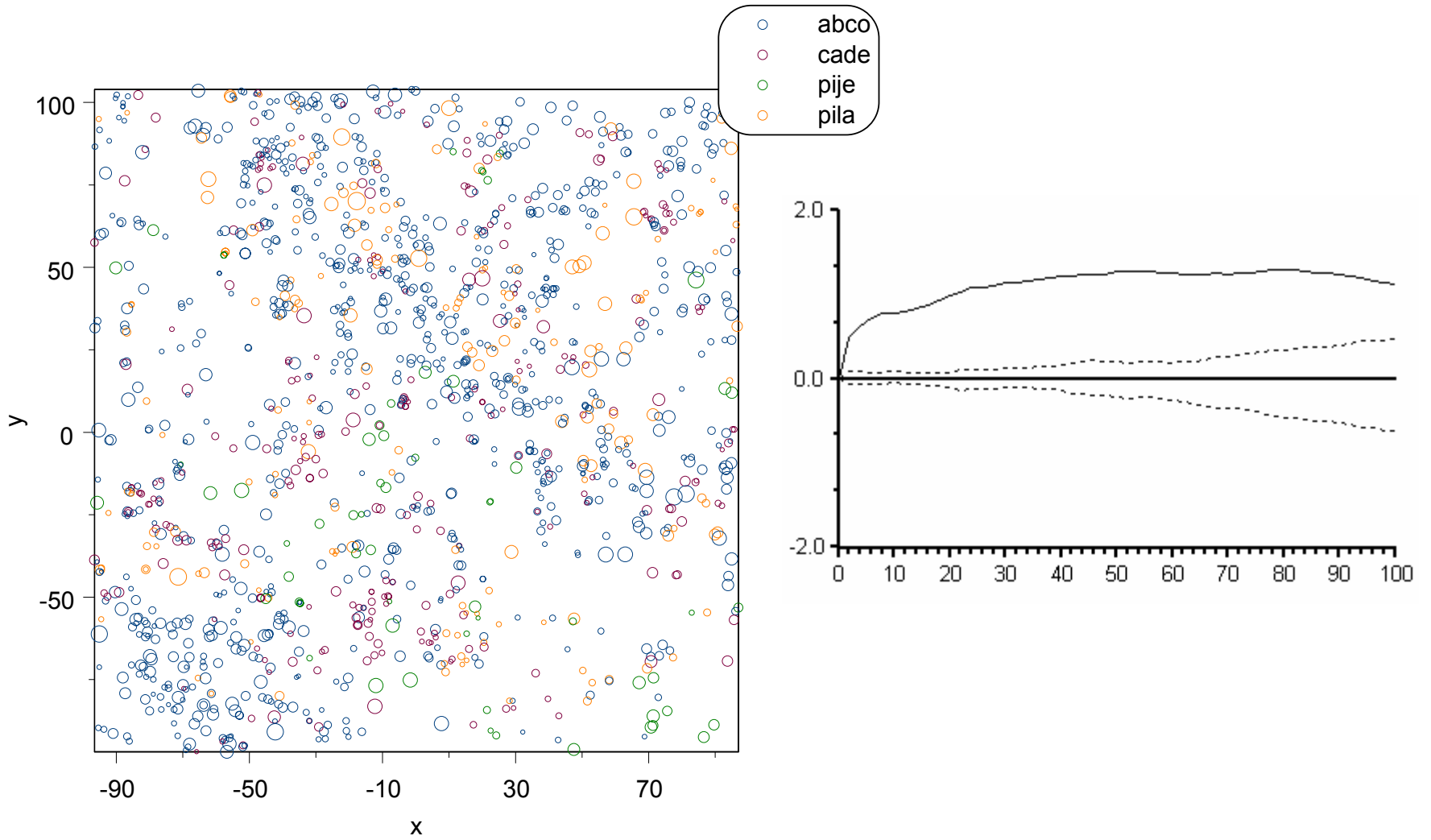
# A: 1865 Reconstruction



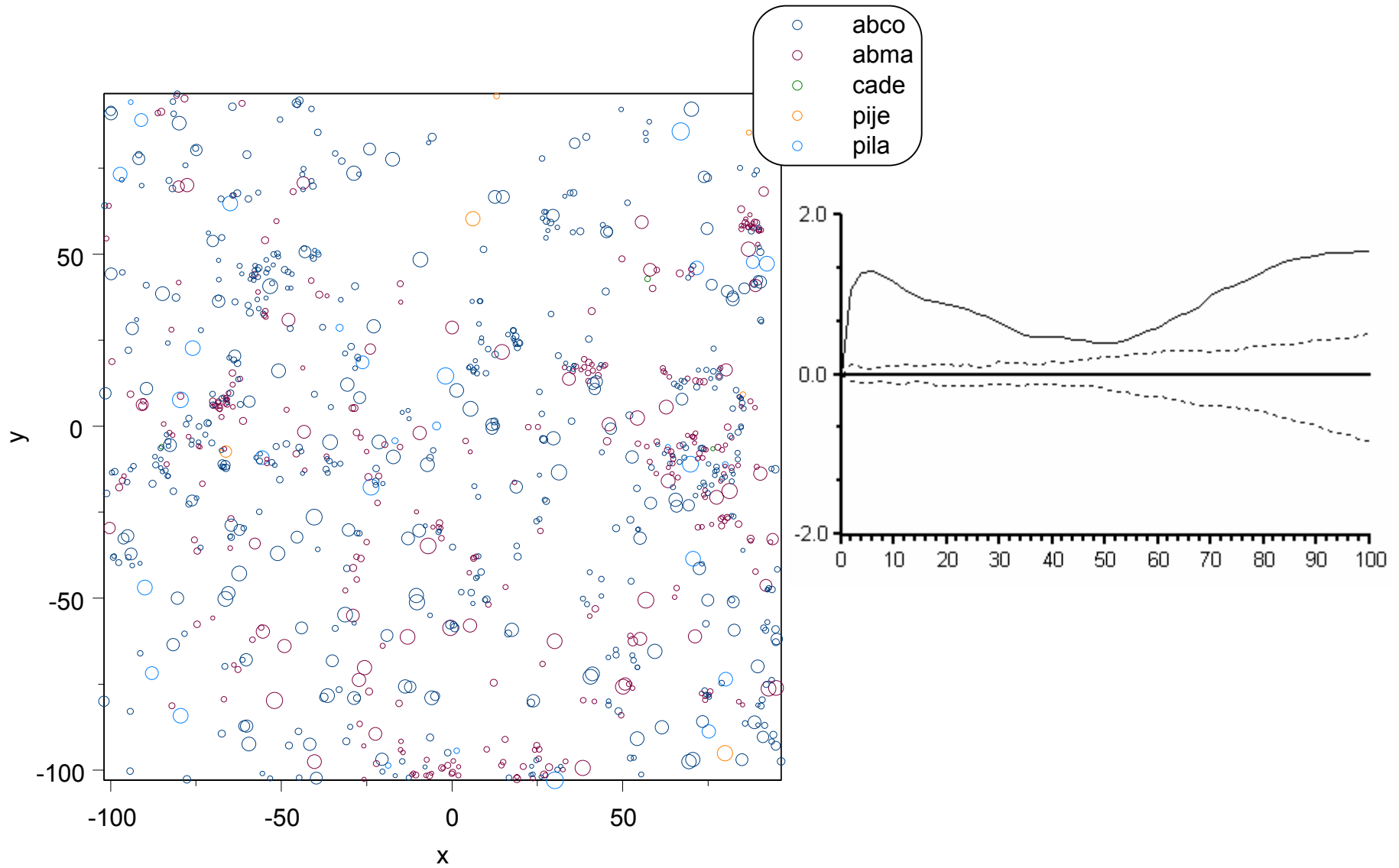
## B: Pretreatment



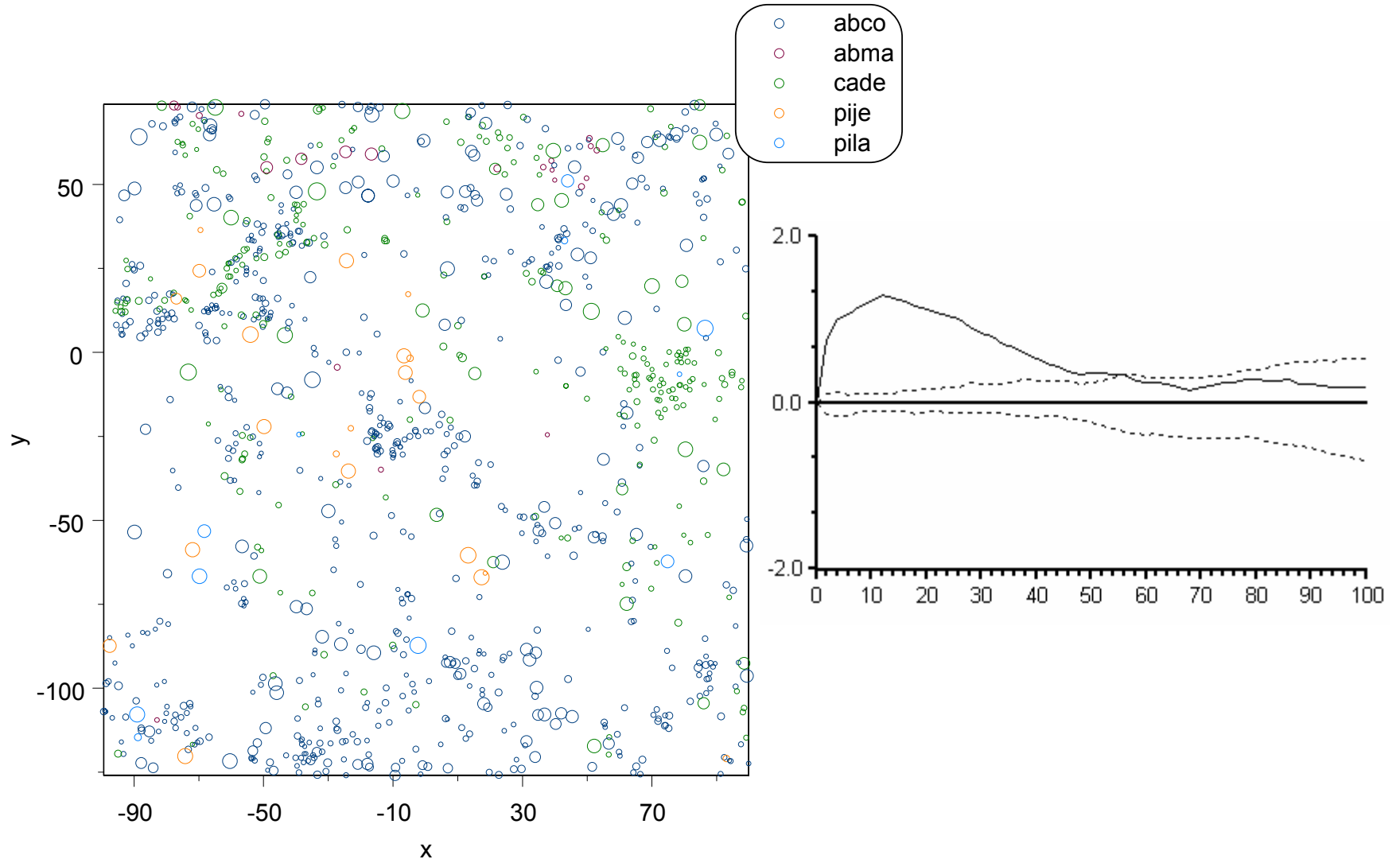
# C: Burn/No Thin



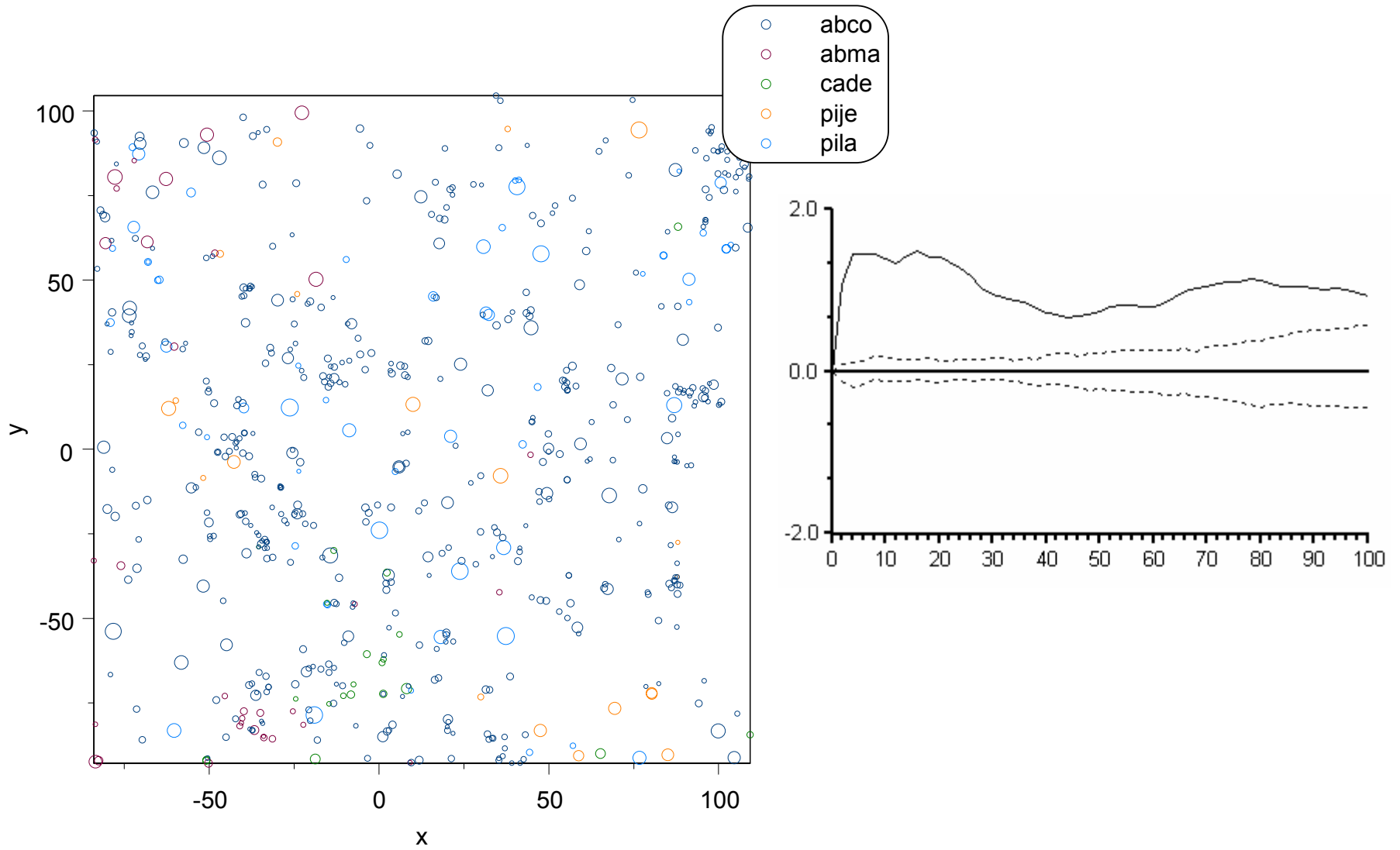
# D: Unburned/Understory Thin



# E: Burn/Understory Thin



# F: Unburned/Overstory Thin



# G: Burn/Overstory Thin

