Ecological Forestry Analysis 2

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Contents

1 Purpose

The goal of this script is to analyze overstory data from the ecological forestry experiment at the Jones Center at Ichauway. Briefly, the experiment began in 2009 when 4 silvicultural treatments varying in spatial pattern were implemented in 18 4 ha mapped longleaf pine dominated stands. The stands were mapped, identified and measured in 2009 (pre-treatment), 2010 (post-treatment), 2014, and 2019.

The objectives of the analysis are to:

- determine the extent to which the treatments vary in structure (BA, density, volume, Dq)
- determine how rates of regeneration and mortality differ among treatments
- determine how treatments vary in spatial structure
- determine how regeneration and mortality processes vary spatially among treatments

2 Data cleanup and summary

- Create tabular summary of treatments for easy merging/analysis

Table 1: Experimental design summary

PLOT	Treatment	Block
1	Control	1
2	Individual	1
3	Group+reserves	1
4	Individual	2
5	Group+reserves	2
6	Group	2
7	Group	3
8	Control	3
9	Individual	3
10	Individual	4
11	Group+reserves	4
12	Group	4
13	Individual	5
14	Group	5
15	Control	5
16	Individual	6
17	Control	6
18	Group+reserves	6

- Create a master tree list from all observation years for quick summary of data by year

Table 2: Example data of master tree list

PLOT	TAGNO	SPECIES	DBH	HEIGHT	year
1	1	PIPA	53.8	27.85	2009
1	2	QUVI	32.4	18.65	2009
1	3	PIPA	57.3	26.25	2009
1	4	PIPA	34.5	24.60	2009
1	5	PIPA	43.9	27.00	2009
1	6	PIPA	48.7	26.95	2009
1	7	PIPA	49.6	29.20	2009
1	8	PIPA	50.6	27.20	2009
1	9	PIPA	59.0	27.20	2009
1	10	PIPA	55.0	28.40	2009
1	11	PIPA	48.5	28.20	2009
1	12	PIPA	46.9	26.35	2009
1	13	PIPA	33.9	25.40	2009
1	14	PIPA	23.3	21.75	2009
1	15	PIPA	17.7	18.50	2009

- Identify recruitment and mortality events

Table 3: Number of mortality events noted in 2014 and 2018

m_yr	Freq
2014	425
2018	599
NA	10949

Table 4: Number of recruitment events noted in 2014 and 2018

r_yr	Freq
2014	662
2018	702
NA	10609

- Setup and apply basal area and biomass functions

I set up several functions to aid in calculation of forest metrics. Two functions aid with calculation of timber volume for longleaf pine. The functions derived from Gonzalez-Benecke et al. (2014) are `Vib4()` and `Vib1()`. $V_{IB}4$ is the stem volume inside bark when dbh and H (height) are known. $V_{IB}1$ is the stem volume inside bark when only dbh is known. I also calculated quadratic mean diameter using the summation method (Shaw 2000).

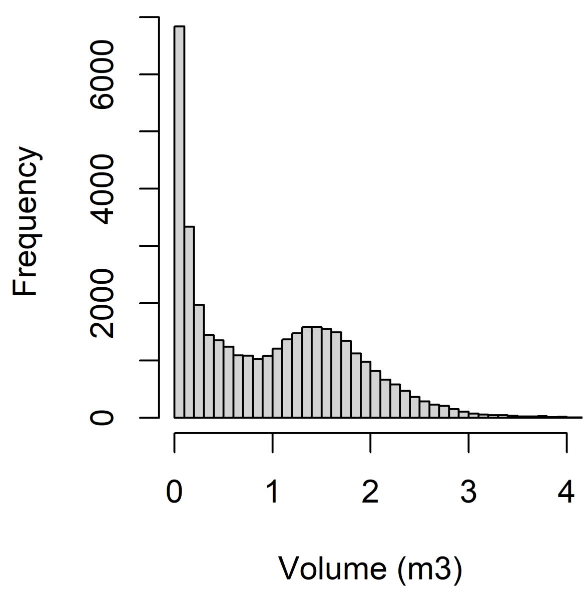

Figure 1: Histogram of tree volume calculated within Ecological forestry plots

Table 5: Species composition of overstory trees based on basal area (m^2 ha^{-1}) and proportion of basal area.

SPECIES	ba	p
PIPA	14.18	94.7
QUVI	0.27	1.8
QUFA	0.19	1.3

SPECIES	ba	p
PIEL	0.13	0.9
QUST	0.06	0.4
QUNI	0.05	0.4
QUHE	0.04	0.2
PRSE	0.02	0.1
PIEC	0.02	0.1
PITA	0.01	0.1
QUIN	0.01	0.0
ACRU	0.00	0.0
CRSPP	0.00	0.0
COFL	0.00	0.0
SAAL	0.00	0.0

Table 6: Percent composition of longleaf pine by plot based on basal area

PLOT	PIPA_ba	tot_ba	p
13	12.25	12.28	99.7
2	17.16	17.28	99.3
12	14.84	15.01	98.9
9	18.49	18.71	98.8
14	12.16	12.31	98.8
11	15.98	16.27	98.2
15	10.65	10.86	98.0
4	15.17	15.54	97.7
10	16.12	16.51	97.6
6	14.65	15.37	95.3
5	14.31	15.15	94.5
16	10.09	10.79	93.5
1	14.59	15.73	92.8
17	11.41	12.41	91.9
18	11.22	12.42	90.4
7	15.47	17.61	87.8
3	15.01	17.11	87.8
8	15.65	18.16	86.2

3 Non-spatial structural changes

3.1 Calculate density changes by plot

Table 7: Changes in non-spatial structural metrics by plot and year. Column `rel_year` represents number of years prior to treatment implementation (2010).

PLOT	year	dens_ha	ba_ha	pipa_vol_ha	dq	Treatment	Block	rel_year
1	2009	143.00	15.73	138.44	37.43	Control	1	-1
1	2010	143.00	15.73	138.44	37.43	Control	1	0
1	2014	143.50	16.58	148.50	38.36	Control	1	4
1	2018	143.75	17.86	159.09	39.78	Control	1	8
8	2009	200.75	18.16	144.53	33.94	Control	3	-1
8	2010	200.75	18.16	144.53	33.94	Control	3	0
8	2014	204.00	19.51	163.00	34.90	Control	3	4
8	2018	193.25	20.62	175.74	36.86	Control	3	8
15	2009	80.25	10.86	99.58	41.51	Control	5	-1
15	2010	80.25	10.86	99.58	41.51	Control	5	0
15	2014	90.25	11.85	109.38	40.90	Control	5	4
15	2018	101.00	12.15	110.91	39.14	Control	5	8
17	2009	95.75	12.41	107.75	40.63	Control	6	-1
17	2010	95.75	12.41	107.75	40.63	Control	6	0
17	2014	103.00	13.33	116.73	40.59	Control	6	4
17	2018	115.75	14.15	125.99	39.45	Control	6	8
6	2009	129.75	15.37	139.60	38.83	Group	2	-1
6	2010	112.50	13.49	121.72	39.07	Group	2	0
6	2014	107.75	13.94	125.86	40.58	Group	2	4
6	2018	97.00	12.94	121.21	41.22	Group	2	8
7	2009	203.75	17.61	144.32	33.17	Group	3	-1
7	2010	186.25	15.99	129.58	33.06	Group	3	0
7	2014	188.50	17.37	144.09	34.26	Group	3	4
7	2018	175.75	17.50	147.33	35.61	Group	3	8
12	2009	184.25	15.01	139.60	32.20	Group	4	-1
12	2010	174.75	13.65	127.35	31.53	Group	4	0
12	2014	186.00	14.77	141.92	31.79	Group	4	4
12	2018	193.75	15.89	148.83	32.32	Group	4	8
14	2009	91.50	12.31	115.81	41.40	Group	5	-1
14	2010	76.00	10.15	94.93	41.23	Group	5	0
14	2014	79.00	10.98	102.03	42.07	Group	5	4
14	2018	92.75	11.56	108.30	39.83	Group	5	8
3	2009	194.25	17.11	140.48	33.49	Group+reserves	1	-1
3	2010	175.25	15.77	128.64	33.85	Group+reserves	1	0
3	2014	179.25	16.73	141.45	34.47	Group+reserves	1	4
3	2018	175.50	17.02	145.12	35.14	Group+reserves	1	8
5	2009	135.75	15.15	133.69	37.70	Group+reserves	2	-1
5	2010	123.25	13.69	119.37	37.60	Group+reserves	2	0
5	2014	124.00	14.71	129.63	38.86	Group+reserves	2	4
5	2018	106.50	12.99	116.84	39.41	Group+reserves	2	8
11	2009	199.25	16.27	151.02	32.25	Group+reserves	4	-1
11	2010	168.75	13.75	127.28	32.20	Group+reserves	4	0
11	2014	196.25	15.47	146.42	31.68	Group+reserves	4	4

PLOT	year	dens_ha	ba_ha	pipa_vol_ha	dq	Treatment	Block	rel_year
11	2018	205.50	16.19	156.17	31.67	Group+reserves	4	8
18	2009	139.25	12.42	96.62	33.69	Group+reserves	6	-1
18	2010	105.00	9.79	73.89	34.45	Group+reserves	6	0
18	2014	110.00	10.63	84.00	35.08	Group+reserves	6	4
18	2018	120.75	11.16	88.09	34.30	Group+reserves	6	8
2	2009	155.25	17.28	167.03	37.65	Individual	1	-1
2	2010	115.75	14.65	142.51	40.14	Individual	1	0
2	2014	112.00	15.21	150.17	41.59	Individual	1	4
2	2018	118.75	15.90	158.23	41.28	Individual	1	8
4	2009	125.75	15.54	148.26	39.66	Individual	2	-1
4	2010	100.25	13.82	132.66	41.89	Individual	2	0
4	2014	100.25	14.59	141.66	43.05	Individual	2	4
4	2018	100.25	14.74	143.53	43.26	Individual	2	8
9	2009	218.25	18.71	175.80	33.03	Individual	3	-1
9	2010	143.00	15.44	147.28	37.08	Individual	3	0
9	2014	135.50	15.94	157.04	38.70	Individual	3	4
9	2018	91.50	11.81	117.36	40.54	Individual	3	8
10	2009	202.50	16.51	153.04	32.22	Individual	4	-1
10	2010	136.50	13.97	131.82	36.10	Individual	4	0
10	2014	129.75	14.69	139.76	37.96	Individual	4	4
10	2018	144.50	15.93	154.78	37.47	Individual	4	8
13	2009	84.50	12.28	116.13	43.02	Individual	5	-1
13	2010	63.50	10.02	95.17	44.81	Individual	5	0
13	2014	66.25	10.70	101.26	45.35	Individual	5	4
13	2018	80.75	11.41	110.96	42.41	Individual	5	8
16	2009	76.50	10.79	93.48	42.38	Individual	6	-1
16	2010	63.50	9.32	80.16	43.22	Individual	6	0
16	2014	68.00	9.96	85.85	43.19	Individual	6	4
16	2018	78.50	10.31	88.30	40.90	Individual	6	8

3.2 Harvest summary

To characterize the impact of the 2009 harvest, I calculated several changes including change in basal area by plot, residual basal area by plot.

Basal area removed from plots was -13.8 % ± 4.1 % and ranged from -7.8 % to -21.2 % removed. Residual basal area was relatively consistent within blocks, with a mean within-block basal area had a range of NA ± NA m^2 ha^{-1}.

3.3 Analysis of structural changes

3.3.1 Harvest effects

First I'd like to analyze effects of harvest on main structural metrics including stem density, basal area, *P. palustris* volume, and *Dq*. I will use repeated measures ANOVA on the 2009 and 2010 comparisons to show effects of harvest. to test whether treatments differentially changed elements of forest structure, I will include a random effect for plot, block effect, and Treatment × year interaction.

Table 8: ANOVA table of effects for changes in ba-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	1218.94	1	0.000
Treatment	2.65	3	0.448
year	0.00	1	1.000
Block	252.44	5	0.000
Treatment:year	50.57	3	0.000

Table 9: ANOVA table of effects for changes in pipa-vol-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	536.00	1	0.000
Treatment	8.89	3	0.031
year	0.00	1	1.000
Block	105.49	5	0.000
Treatment:year	52.18	3	0.000

Table 10: ANOVA table of effects for changes in dens-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	361.35	1	0.000
Treatment	14.89	3	0.002
year	0.00	1	1.000
Block	334.32	5	0.000
Treatment:year	16.12	3	0.001

Table 11: ANOVA table of effects for changes in dq following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	1460.85	1	0.000
Treatment	17.12	3	0.001
year	0.00	1	1.000
Block	100.02	5	0.000
Treatment:year	42.72	3	0.000

Overall, I found that treatments showed significant treatment $\times$ year interactions for all variables indicating that treatments altered variables relative to controls.

3.3.2 Post-harvest trajectory

Next, I want to use repeated measures ANOVA to compare trajectories of each metric by comparing the 2010 (*post-harvest*) to the data from 2018. I will include the same effects as above. **Note**: Plots 3, 5, and 6 were struck by a tornado in 2017, and these plots were removed from consideration here.

Table 12: ANOVA table indicating changes in ba-ha immediately post-harvest and 8 years post-harvest ba-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	442.95	1	0.000
Treatment	0.51	3	0.917
year	15.80	3	0.001
Block	114.31	5	0.000
Treatment:year	30.56	9	0.000

Table 13: ANOVA table indicating changes in pipa-vol-ha immediately post-harvest and 8 years post-harvest pipa-vol-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	359.00	1	0.000
Treatment	3.85	3	0.279
year	19.91	3	0.000
Block	99.74	5	0.000
Treatment:year	27.00	9	0.001

Table 14: ANOVA table indicating changes in dens-ha immediately post-harvest and 8 years post-harvest dens-ha following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	216.06	1	0.000
Treatment	4.29	3	0.232
year	0.94	3	0.816
Block	251.95	5	0.000
Treatment:year	20.89	9	0.013

Table 15: ANOVA table indicating changes in dq immediately post-harvest and 8 years post-harvest dq following treatments.

	Chisq	Df	Pr(>Chisq)
(Intercept)	1284.56	1	0.000
Treatment	8.50	3	0.037
year	0.36	3	0.949
Block	84.00	5	0.000
Treatment:year	14.61	9	0.102

These analyses show that Treatments changed over time compared to controls for all metrics except for Dq which was relatively constant over time (Fig. 2).

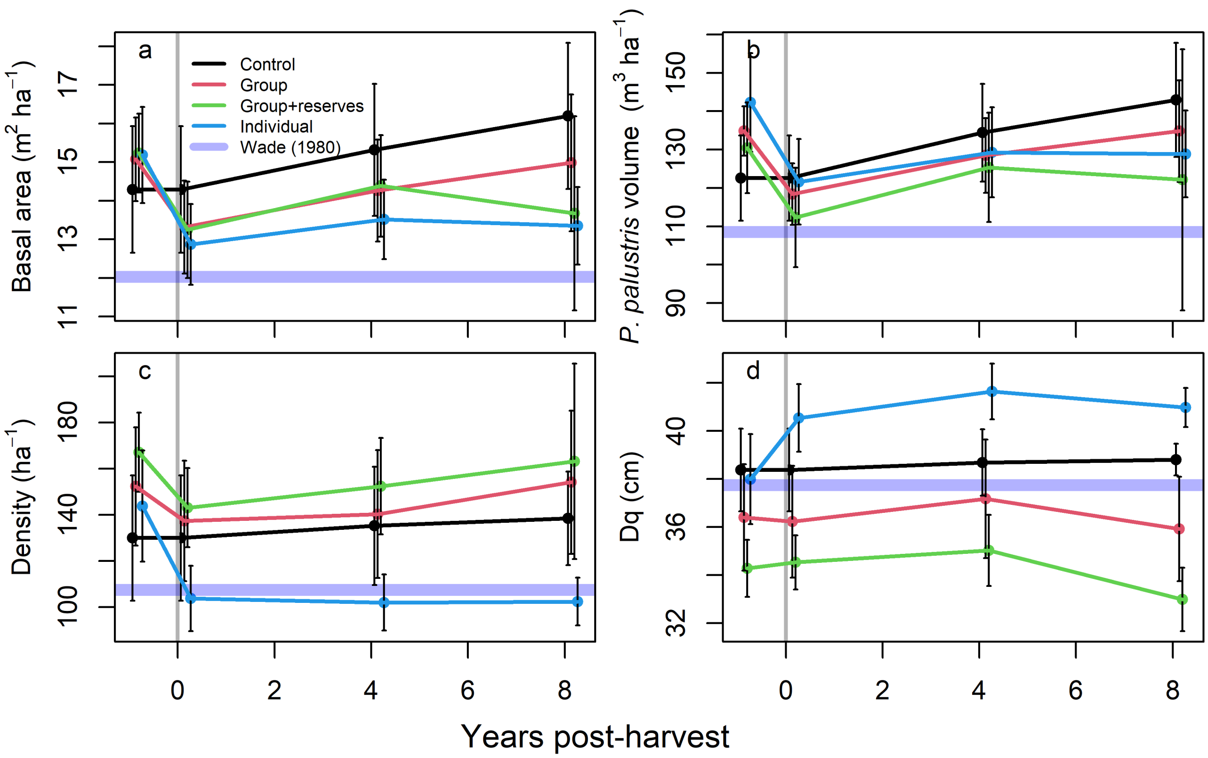

Figure 2: Changes in forest structural components over the 8 year study period indicating changes in (a) density, (b) basal area, (c) *Pinus palustris* volume, and (d) quadratic mean diameter (Dq).

Table 16: Summary of density metrics by silvicultural selection treatment

Treatment	year	ba_ha_mn	pipa_vol_ha_mn	dens_ha_mn	dq_mn
Control	2009	14.29 (3.28)	122.58 (22.23)	129.94 (54.23)	38.38 (3.44)
Control	2010	14.29 (3.28)	122.58 (22.23)	129.94 (54.23)	38.38 (3.44)
Group	2009	15.07 (2.17)	134.83 (12.88)	152.31 (51.23)	36.4 (4.43)
Group	2010	13.32 (2.4)	118.39 (15.99)	137.38 (52.19)	36.22 (4.66)
Group+reserves	2009	15.24 (2.04)	130.45 (23.65)	167.12 (34.3)	34.28 (2.37)
Group+reserves	2010	13.25 (2.5)	112.29 (25.93)	143.06 (34.34)	34.53 (2.26)
Individual	2009	15.18 (3.05)	142.29 (31.47)	143.79 (59.15)	37.99 (4.59)
Individual	2010	12.87 (2.56)	121.6 (27.35)	103.75 (34.67)	40.54 (3.44)

3.4 Diameter distribution

Post harvest density and *Dq* seem to be some of the major changes among treatments. Next I'd like to generate diameter distributions for each plot type to compare how they changed following harvest.

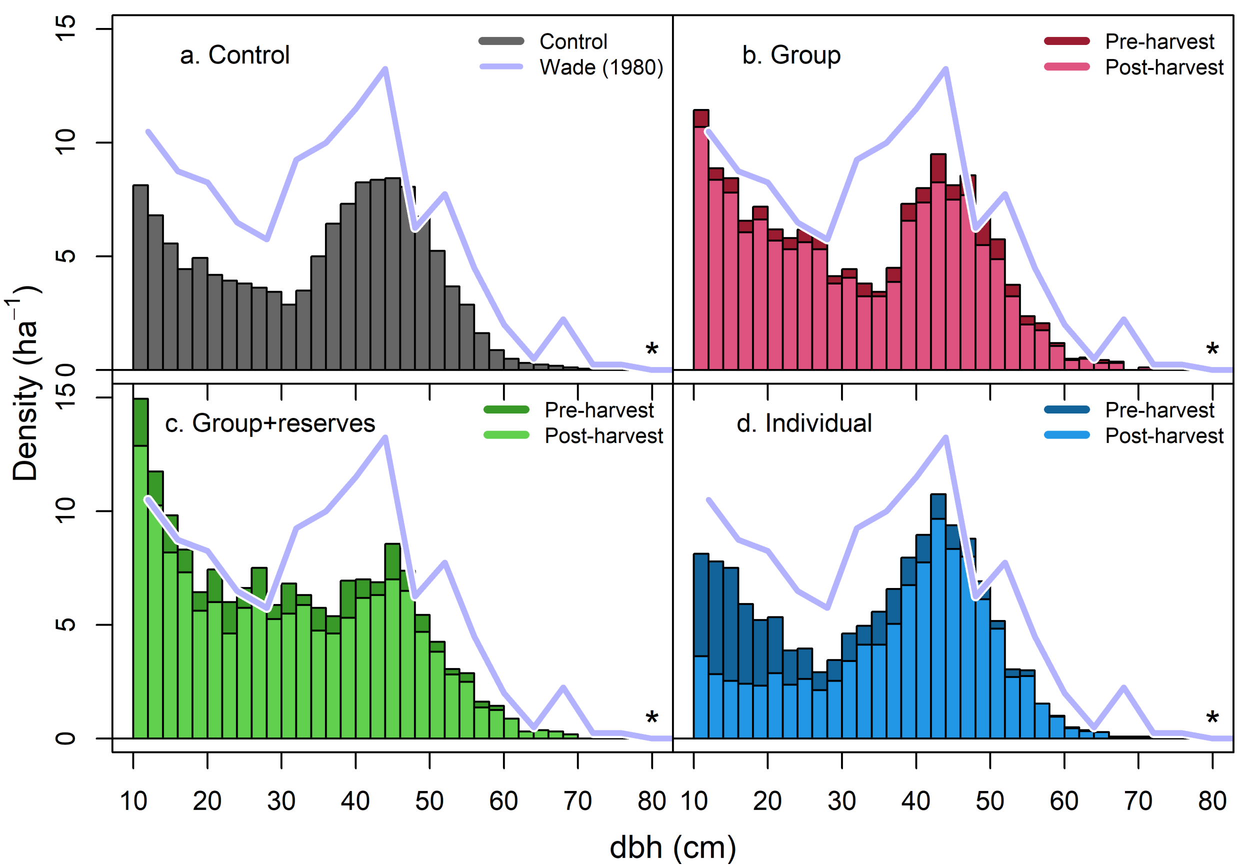

Figure 3: Changes in diameter distribution following harvest for each of four silvicultural treatments including (a) control, (b) group selection, (c) group selection with reserves, and (d) individual tree selection. Dark bars represent pre-treatment distribution and lighter bars represent post-treatment distribution. Note that ten trees $\geq$ 80 cm dbh were omitted for clarity.

Changes in diameter distribution occurred relatively evenly across diameter classes for the group selection and group selection with reserves treatments (but removals of trees with dbh > 60 cm were rare). For these treatments removals in the 10-30 cm ranged were from 8-15%. However, in the Stoddard-Neel selection treatments, removals were high in the 10-30 cm range was 51%, much higher than other treatment types. Figures shows diameters up to 80 m, but though trees > 80 cm were present

Table 17: Total number of trees $\leq$ 30 cm dbh before and after silvicultural treatments and proportion of trees removed.

Treatment	pre_n	pos_n	rm
Control	782	782	0.000
Group	1131	1045	0.076
Group+reserves	1355	1149	0.152
Individual	1298	631	0.514

4 Non-spatial mortality and recruitment rates

- Calculate mortality relative to post-treatment (2010) tree density to generate `dynamics_rel` dataframe Table with absolute recruitment and mortality rates is also retained in the `dyanmics_abs` dataframe.
- **Note** that in all analyses of mortality and recruitment, I ommitted plots 3, 5, and 6 which experienced tornado damage in 2017.

Table 18: Recuritment and mortality rates by treatment and net change. All units are expressed in stems ha^{-1} yr^{-1}.

Treatment	Recruitment rate	Mortality rate	Net change
Control	2.16 (1.37)	1.03 (0.61)	1.13 (1.74)
Group	2.6 (0.81)	1.41 (1.19)	1.2 (1.86)
Group+reserves	4.62 (2.47)	1.3 (0.6)	3.33 (1.88)
Individual	1.9 (1.17)	2.02 (2.48)	-0.11 (3.13)

Table 19: Recuritment and mortality rates by treatment and net change as. All units are expressed as a percentage change from post-harvest (2010) stem density

Treatment	Recruitment rate (%)	Mortality rate (%)	Net change (%)
Control	2.2 (1.89)	0.78 (0.2)	1.42 (1.86)
Group	2.1 (1.21)	0.89 (0.51)	1.22 (1.64)
Group+reserves	3.26 (0.74)	0.93 (0.13)	2.33 (0.6)
Individual	2.17 (1.62)	1.62 (1.63)	0.55 (2.82)

- Analyze recruitment and mortality rates (absolute rates) using ANOVA. There were only a marginally significant ($p = 0.065$) change in recruitment rates, with the Groups + reserves treatment showing the highest rates of recruitment.

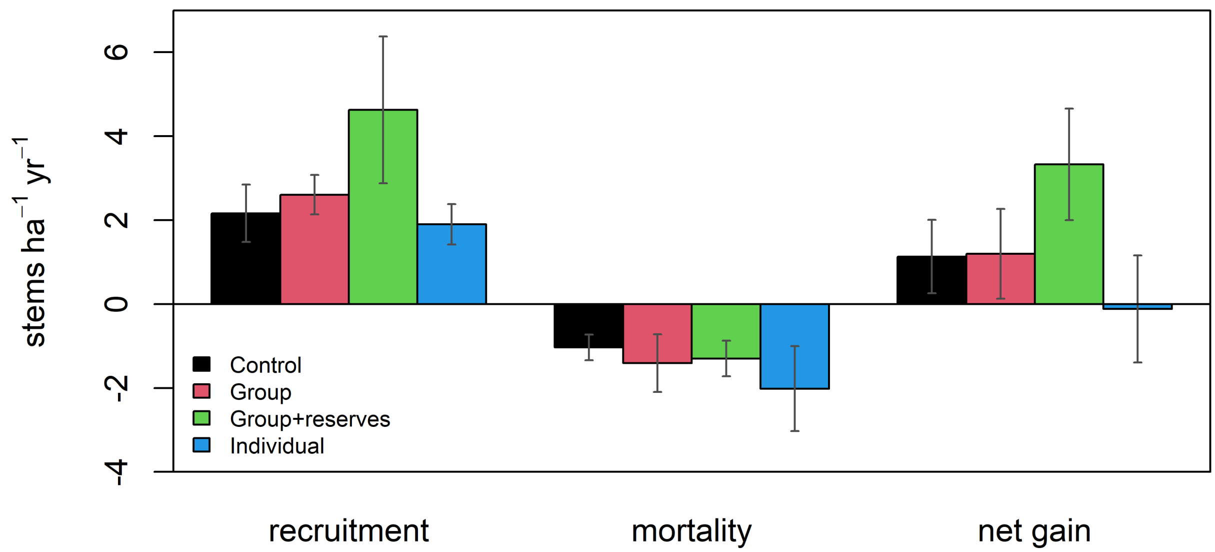

Figure 4: Recruitment, mortality rate, and net change in tree density by treatment. Error bars represent 1 s.e. of the mean.

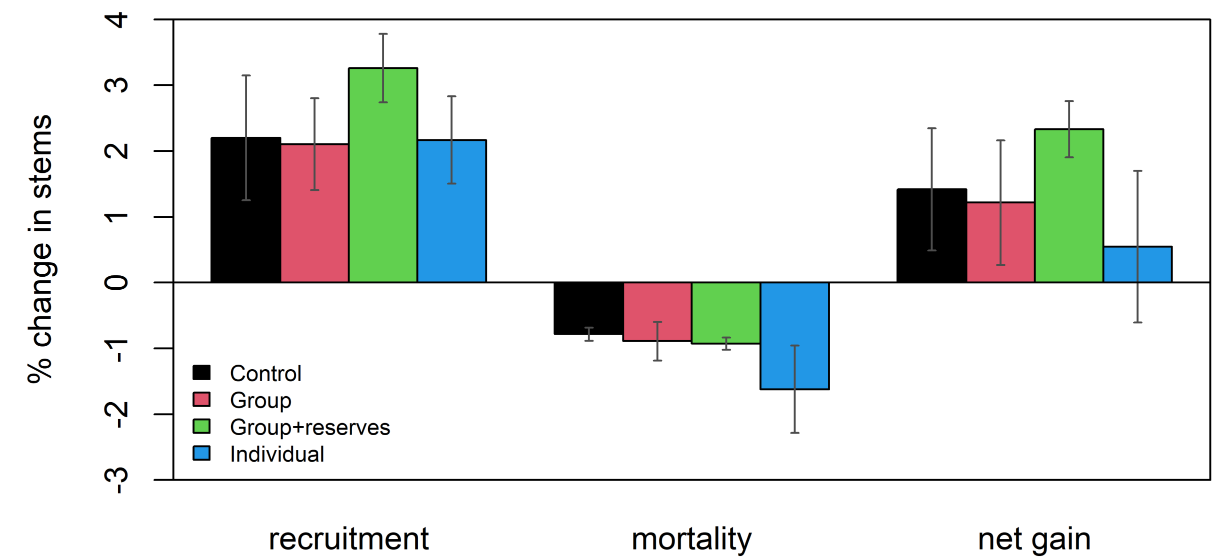

Figure 5: Recruitment, mortality rate, and net change in tree density by treatment as a percentage of post-harvest (2010) density. Error bars represent 1 s.e. of the mean.

Table 20: ANOVA table showing changes in r-abs by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	7.71	2.57	3.44	0.065
Block	5	26.03	5.21	6.97	0.006
Residuals	9	6.72	0.75	NA	NA

Table 21: ANOVA table showing changes in m-abs by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	3.71	1.24	0.65	0.605
Block	5	23.06	4.61	2.40	0.120
Residuals	9	17.26	1.92	NA	NA

Table 22: ANOVA table showing changes in net by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	6.19	2.06	0.77	0.539
Block	5	70.79	14.16	5.28	0.015
Residuals	9	24.11	2.68	NA	NA

- Analyze recruitment and mortality rates (as a percentage) using ANOVA. There were only a marginally significant ($p = 0.065$) change in recruitment rates, with the Groups + reserves treatment showing the highest rates of recruitment.

Table 23: ANOVA table showing changes in p-rec by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	1.16	0.39	0.92	0.47
Block	5	29.87	5.97	14.13	0.00
Residuals	9	3.80	0.42	NA	NA

Table 24: ANOVA table showing changes in p-mor by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	2.01	0.67	0.60	0.633
Block	5	6.55	1.31	1.16	0.396
Residuals	9	10.13	1.13	NA	NA

Table 25: ANOVA table showing changes in p-net by treatment

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	2.32	0.77	0.49	0.700
Block	5	58.38	11.68	7.36	0.005

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Residuals	9	14.28	1.59	NA	NA

- How does mortality vary as a function of size? Does relationship between mortality and size vary by treatment?

There are very few individuals > 70 cm dbh (*i.e.*, four individuals), so I will include only indivudals $\leq 70cm$ in the following analyses and figures.

Table 26: Results of mixed-effects generalized linear model indicating effect of treatment and tree size on mortality rates.

	Chisq	Df	Pr(>Chisq)
dbh_z	23.22	1	0.000
I(dbh_z^2)	44.01	1	0.000
Treatment	0.64	3	0.888
dbh_z:Treatment	15.97	3	0.001
I(dbh_z^2):Treatment	18.58	3	0.000

Table 27: Marginal (R^2_m) and conditional (R^2_c) fits of mixed-effects generalized model.

	R2m	R2c
theoretical	0.089	0.244
delta	0.012	0.033

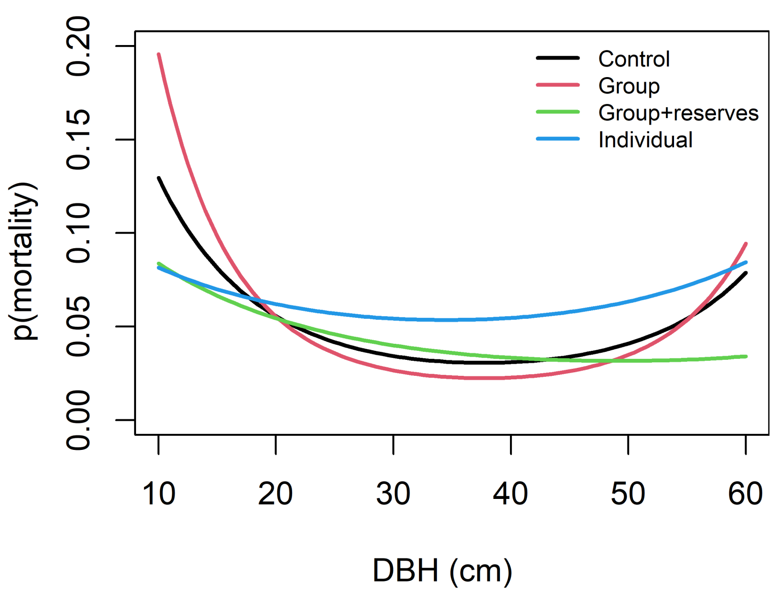

Figure 6: Relationship between mortality and tree diameter among treatments.

5 Changes in spatial structure

In order to determine how silvicultural treatments varied in spatial pattern and how these patterns compared to examples of old-growth forests. I used the `spatstat` package. The goal of these analyses were to use pair correlation functions `spatstat::pcf()` to assess spatial pattern at various scales.

Using 999 simulations, I used the `pcf` function to assess the spatial pattern of trees. To more completely assess the change, I calculated `pcf`s separately for all trees, small trees (dbh < 30), medium trees ($30 \leq$ dbh < 50), and large trees (dbh ≥ 50).

In the controls, I found high spatial clustering at small scales (Figure 7a). Clustering was higher for small trees, and diminished with larger trees (Figure 7e,i,m). Treatments generally slightly increased spatial clustering overall (Figure 7b,c), and for individual tree size classes (e.g., Figure 7f,j,h). However, a notable exception is the Individual tree selection treamtn whichwhere clustering decreased overall, especially at small scales (Figure 7d). This was primarily due to reduction in clustering of the 30-50 cm size class (Figure 7l).

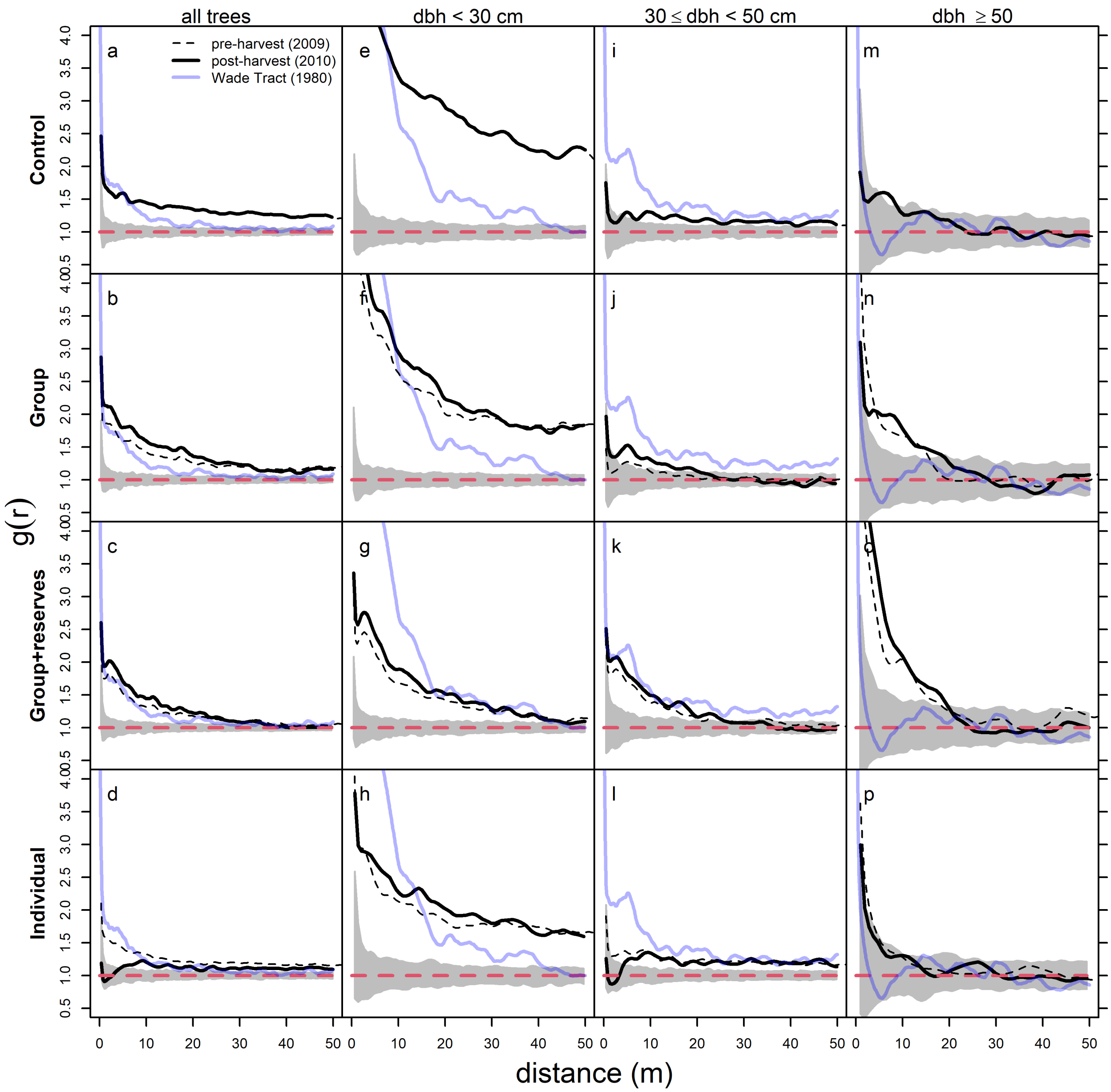

Figure 7: Pair correlation functions illustrating changes in spatial pattern of overstory trees before (2009, solid line) and after (2010, dashed line) four silvicultural selection treatments. Shading represents expectation under complete spatial randomness generated from 999 simulations of the 2010 data. Portions of each function above or below shading represents significant aggregation or over-dispersion, respectively, and portions of the function within the grey shading represent random dispersion of tree locations.

6 Spatial patterns of mortality and recruitment

How does the spatial pattern of new recruits change across treatments?

How does the spatial pattern of mortality events change across treatments?

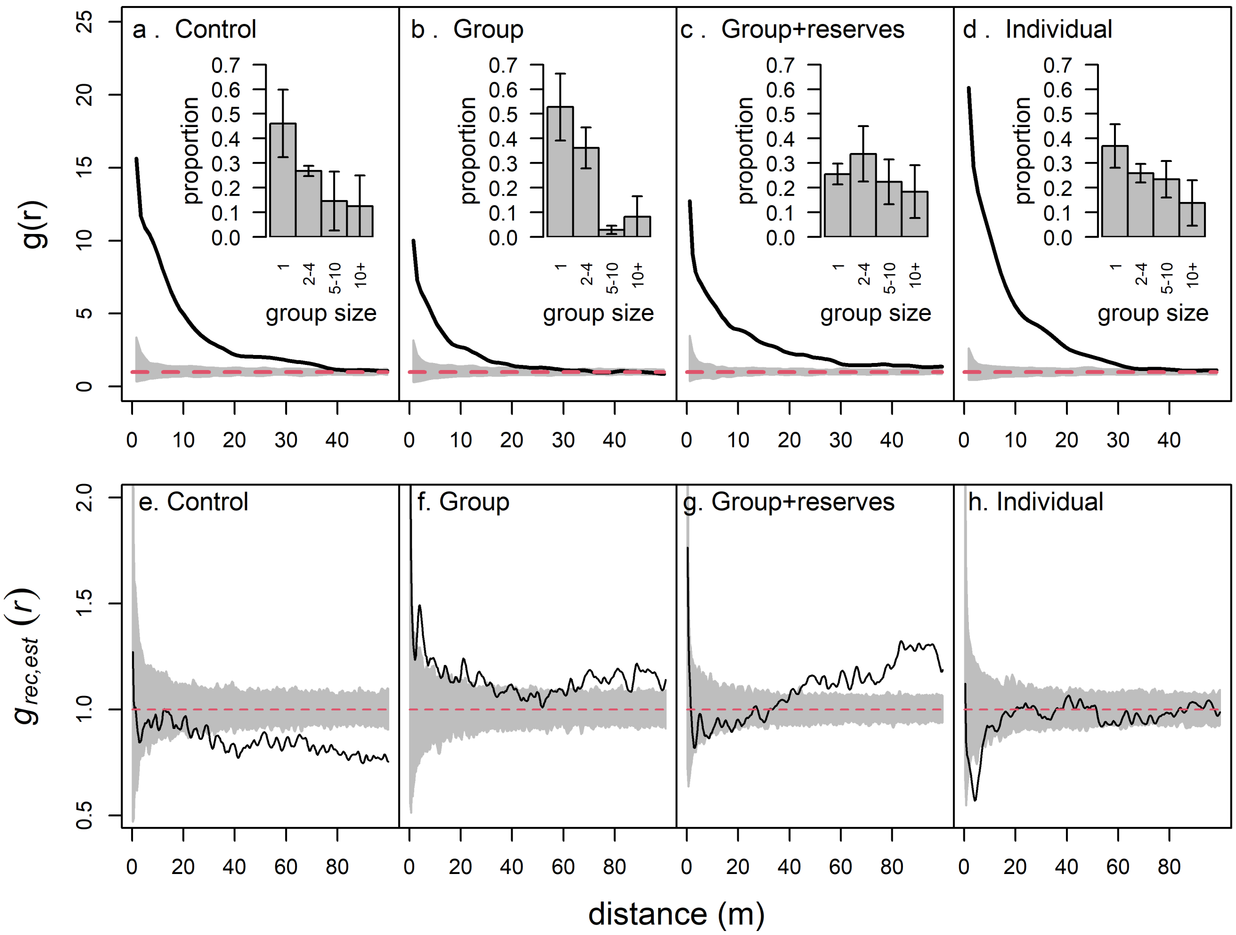

Figure 8: (a-d) Pair correlation functions illustrating spatial pattern of individual trees that recruited between 2009 and 2019 tree surveys illustrating strong clumping of regeneration across scales for all treatments. Shading represents expectation under complete spatial randomness generated from 999 simulations. Interpretation as in Figure 4. Inset barplots indicate the distribution of newly recruited trees based on group size with trees within 6 m considered a contiguous group. (e-h) Marked pair correlations functions showing the spatial associations between newly recruited (rec) and already established (est) individuals.

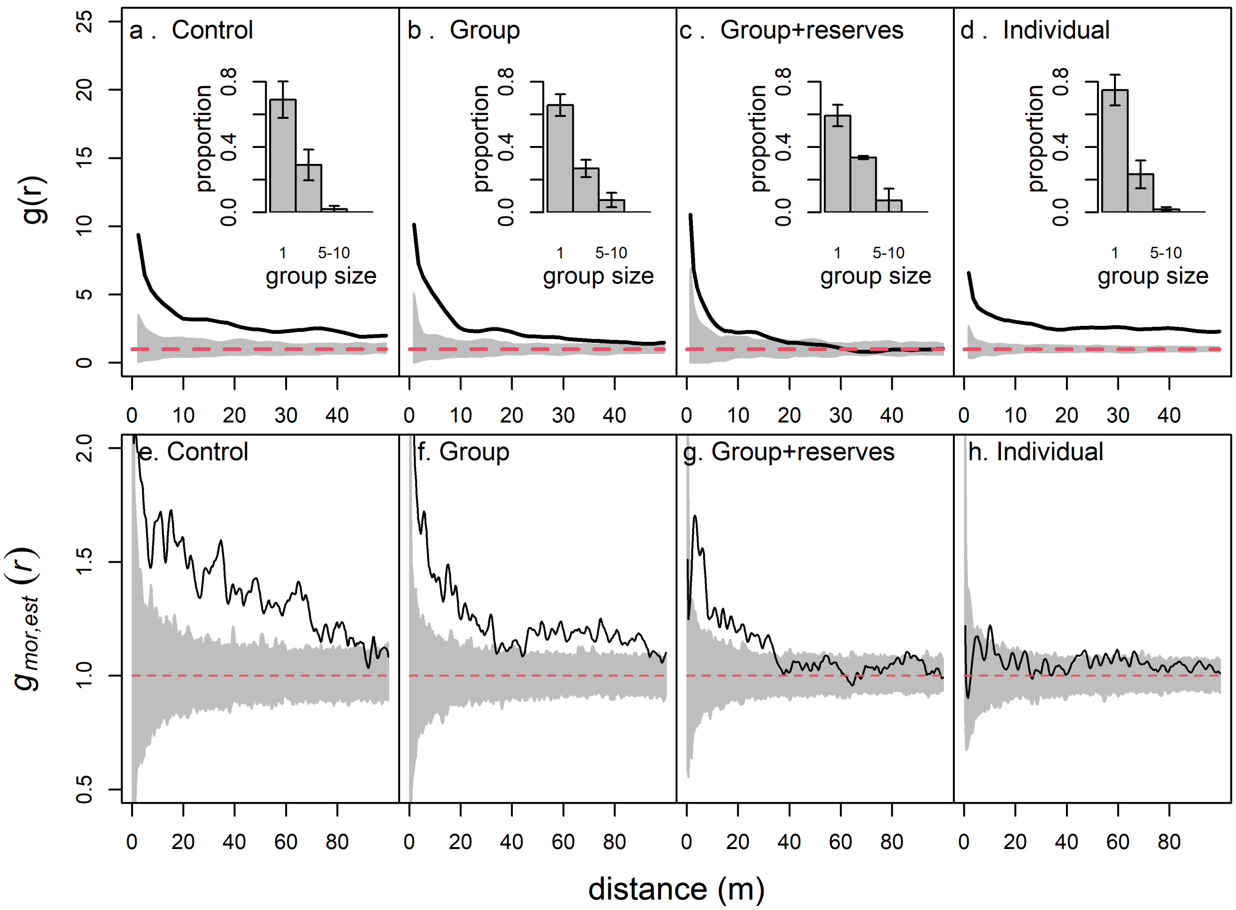

Figure 9: (a-d) Pair correlation functions illustrating spatial pattern of trees that died between 2009 and 2019 tree surveys illustrating strong clumping of mortality across scales for all treatments. Shading represents expectation under complete spatial randomness generat ed from 999 simulations. Interpretation of clustering as in Figure 3. Inset barplots indicate the group size of dead trees considering dead trees within 6 m as a contiguous group. (e-h) Marked pair correlations functions showing the spatial associations between dead trees (mor) and already established (est) individuals.

Literature Cited

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