

# Analysis of Uncertainty in Co-Exposure Models

White Paper

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National Institute for Occupational  
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Nancy Chalmers  
Oak Ridge Associated Universities Team

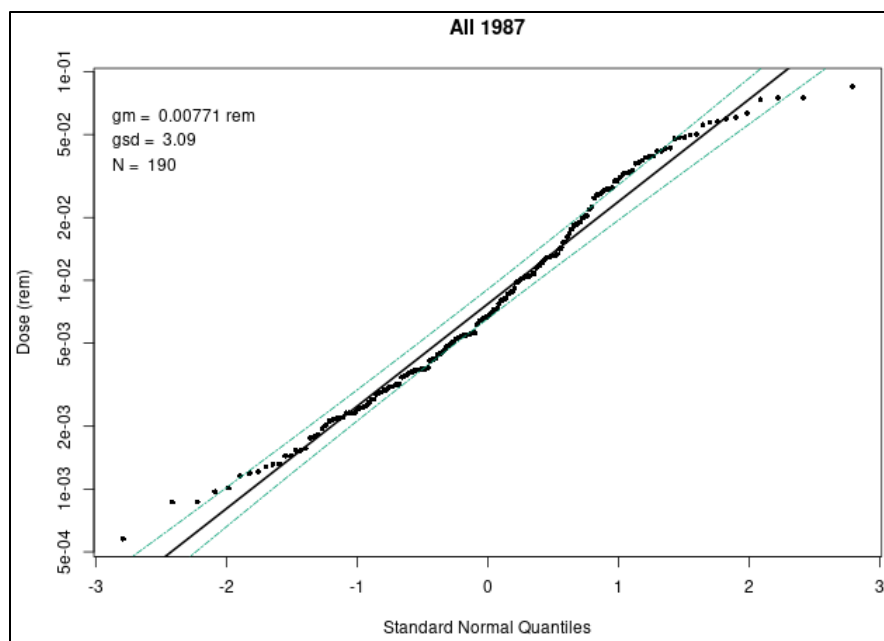
Reviewed by John Cardarelli II and Timothy Taulbee  
Division of Compensation Analysis and Support

## INTRODUCTION

The goal of a co-exposure study as used in the Energy Employees Occupational Illness Compensation Act program is to define the probability distribution of doses to a *target population* [Coggon et al. 2009], which in this discussion is all workers exposed to tritiated water in a given year during the course of their work at the Savannah River Site (SRS). This probability distribution is referred to as a co-exposure model, which is used to assign probability-based doses to members of the target population who were not monitored but may have been exposed. All members of the target population who were monitored are referred to as the *study population*. A representative sample of the study population is called the *study sample*.

The co-exposure model is constructed from the study sample, which in this discussion consists of the tritium dose data from SRS workers who filed a claim in the compensation program, i.e., doses from the National Institute for Occupational Safety and Health (NIOSH) Division of Compensation Analysis and Support (DCAS) Claims Tracking System (NOCTS). This is the same tritium dataset used in the tritium co-exposure models in ORAUT-OTIB-0081, *Internal Dosimetry Co-Exposure Data for the Savannah River Site* [ORAUT 2020]. As discussed in ORAUT-OTIB-0075, *Use of Claimant Datasets for Coworker Modeling* [ORAUT 2016], NOCTS bioassay results and doses are considered to be equivalent to simple random samples from the study population. Note that the SRS NOCTS tritium data for 1987 and 1980 are used here to illustrate certain concepts concerning stratification of co-exposure models. The objective of this paper is to assess the quality of the inferences made from co-exposure models.

The most basic graphical representation of a co-exposure model is a lognormal quantile-quantile (QQ) plot like the one shown in Figure 1. This plot consists of all tritium doses for 190 workers in 1987 that are sorted (i.e., calculate the order statistics), plotted against the standard normal quantiles, and fit with a straight line. The slope of the line is the log of geometric standard deviation (GSD) of the lognormal distribution, and the intercept is the log of the geometric mean (GM) of the lognormal distribution. Given this co-exposure model, one can, for example, assign the 50th percentile dose of 7.7 mrem to an unmonitored worker from the target population.



**Figure 1. NOCTS tritium doses for SRS workers monitored in 1987 (black dots). The black line is the regression on the order statistics from which the GM and GSD are calculated. The dashed lines are the 95% confidence band for the regression line.**

The slope and intercept have associated uncertainties resulting from things like the measurement uncertainties in the tritium dose and the use of the study sample to describe the target population (the sampling error). In practice, the uncertainties in the slope and intercept are not considered in the compensation program. For the purpose of this discussion, the 95% confidence band of the black line in Figure 1 was calculated using the bootstrap method<sup>1</sup> [Efron and Tibshirani 1994] and is presented as the two dashed lines. One can reasonably expect the line defined by the unknown true values of the GM and GSD (i.e., the GM and GSD of the target population) to fall between the two dashed lines.

If the target population consists of subgroups whose dose distributions differ greatly, the co-exposure model should be stratified, giving each of these groups their own co-exposure model [Scheaffer et al. 2011]. Properly constructed stratified co-exposure models are, in general, more accurate and can be expected to give 95% confidence bands that are narrower than the bands seen with the unstratified model. This is why co-exposure models should be stratified when appropriate. However, if the co-exposure model is stratified and the subgroups have essentially the same dose distributions or if stratification reduces the number of doses in each stratum,

<sup>1</sup>A bootstrap sample is a random sample of our original sample, the same size as the original sample, taken with replacement. A sample taken with replacement means that a given item in the original sample can appear more than once in the bootstrap sample. The basic idea is to take many bootstrap samples and calculate the statistic of interest (like the mean) for each bootstrap sample. The distribution of the means of the bootstrap samples is an estimate of the uncertainty in the mean calculated with the original sample. This approach is often used to calculate uncertainties in statistics that are difficult or impossible to calculate using traditional methods.

stratification will increase the uncertainty in the co-exposure models compared with the unstratified co-exposure model. The purpose of this discussion is to provide examples that illustrate these concepts.

### **UNCERTAINTY ANALYSIS OF TRITIUM CO-EXPOSURE MODELS FOR 1987**

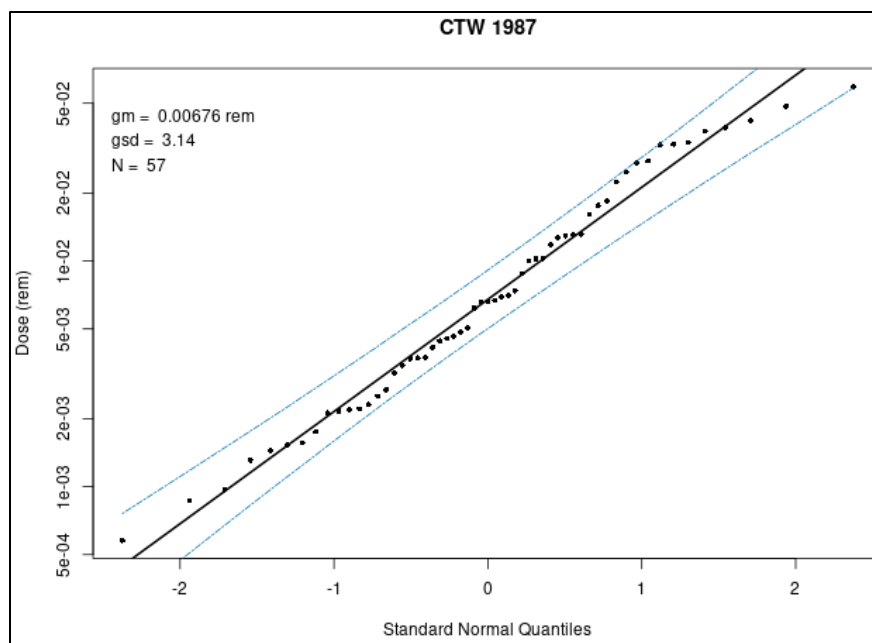
The previous section mentioned properly constructed stratified co-exposure models, which means that:

- The strata are defined before samples are taken.
- All workers in the study population are placed in the appropriate strata, with each worker in only one stratum.
- The size of the study samples taken from each stratum is determined before the samples are taken.
- There are indeed differences between the distributions of the doses in the strata that are of practical significance.

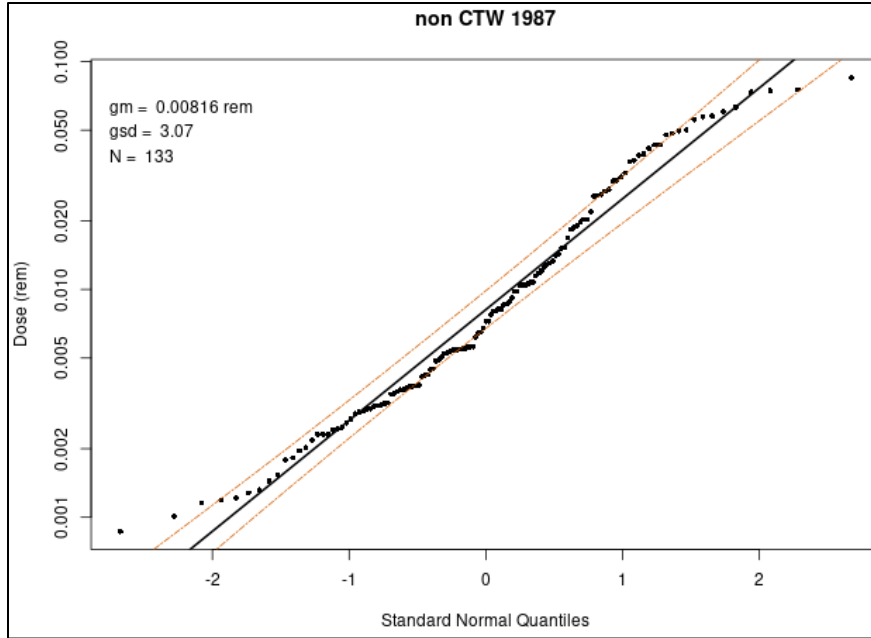
The stratified sampling used for developing co-exposure models frequently does not strictly adhere to these conditions, because NOCTS samples are simple random samples that are stratified after collection, which is referred to as *poststratification*. For example, the study sample of 190 workers in 1987 was stratified into 57 construction trade workers (CTW) and 133 nonconstruction trade workers (nonCTW) after the NOCTS sample was collected. In general, the uncertainty in co-exposure models derived using poststratification is greater than that obtained using prestratification.

The co-exposure model for CTWs is shown in Figure 2, where the dashed lines denote the 95% confidence bands on the black regression line. Likewise, the co-exposure model for the nonCTWs is shown in Figure 3, where the dashed lines denote the 95% confidence bands on the black regression line. The GMs and GSDs for the combined and stratified models appear to be quite similar. The confidence bands for all three models are shown together in Figure 4, for which one can conclude that

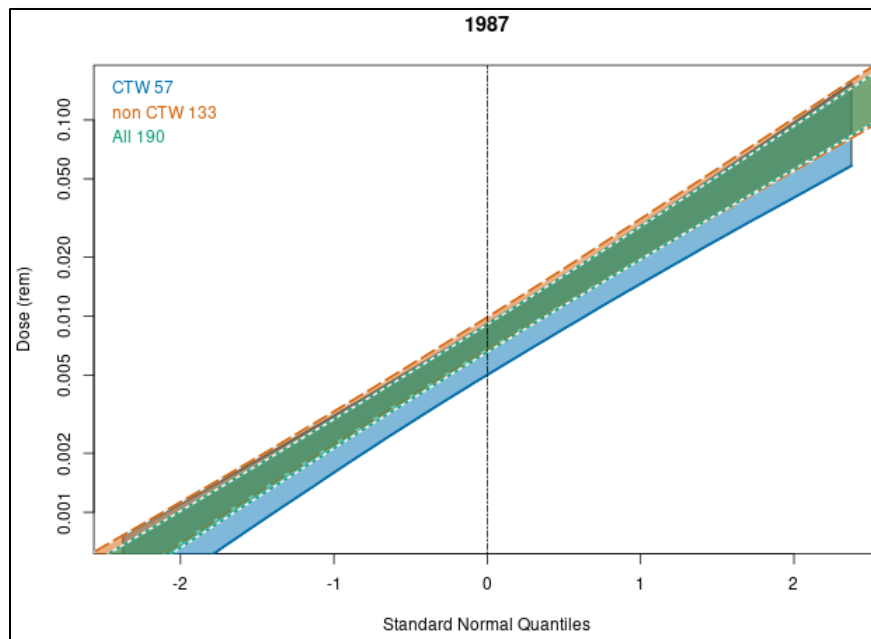
- The three 95% confidence bands overlap in the entire range of the observed data.
- The confidence bands for the co-exposure model constructed from all 190 doses is narrower than the confidence bands for the stratified co-exposure models.



**Figure 2. NOCTS tritium doses for SRS CTWs monitored in 1987 (black dots). The black line is the regression on the order statistics from which the GM and GSD are calculated. The dashed lines are the 95% confidence band for the regression line.**



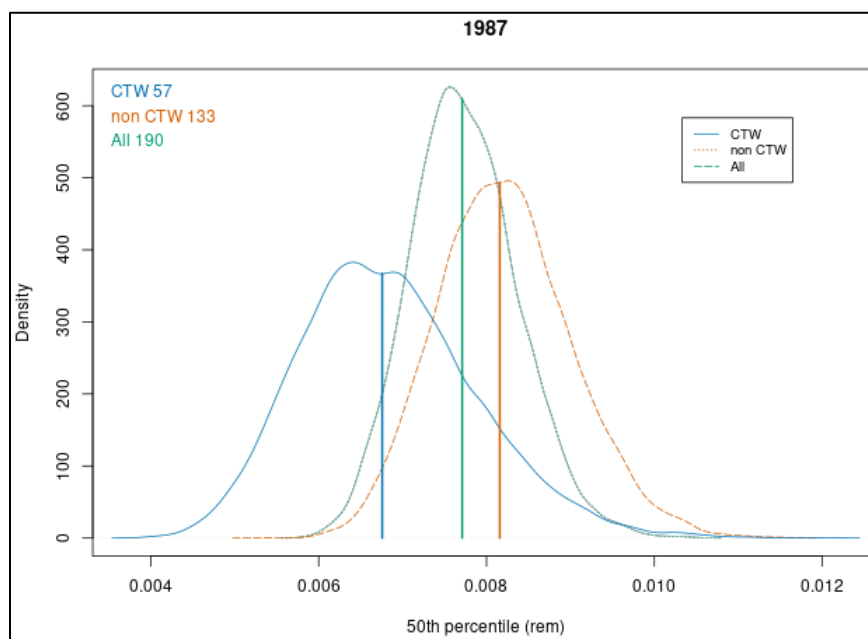
**Figure 3. NOCTS tritium doses for SRS nonCTWs monitored in 1987 (black dots). The black line is the regression on the order statistics from which the GM and GSD are calculated. The dashed lines are the 95% confidence band for the regression line.**



**Figure 4. Confidence bands for all workers, CTWs, and nonCTWs for 1987. The vertical dashed line is the median (50th percentile) of the distributions.**

Although not a formal statistical test, the distributions of all three models can be considered to be the same for all practical intents and purposes. This becomes even more apparent if we take a slice of the distributions in Figure 4 at the 50th percentile (the vertical dashed line) and present these data as density plots (Figure 5). The density plots present the same message as the confidence bands with a bit more clarity:

- The three probability density curves overlap to a large extent.
- The probability density curve for the 50th percentile from the full co-exposure model calculated with all 190 doses is narrower (lower uncertainty) than the distributions of the 50th percentiles calculated from the stratified CTW and nonCTW co-exposure models.



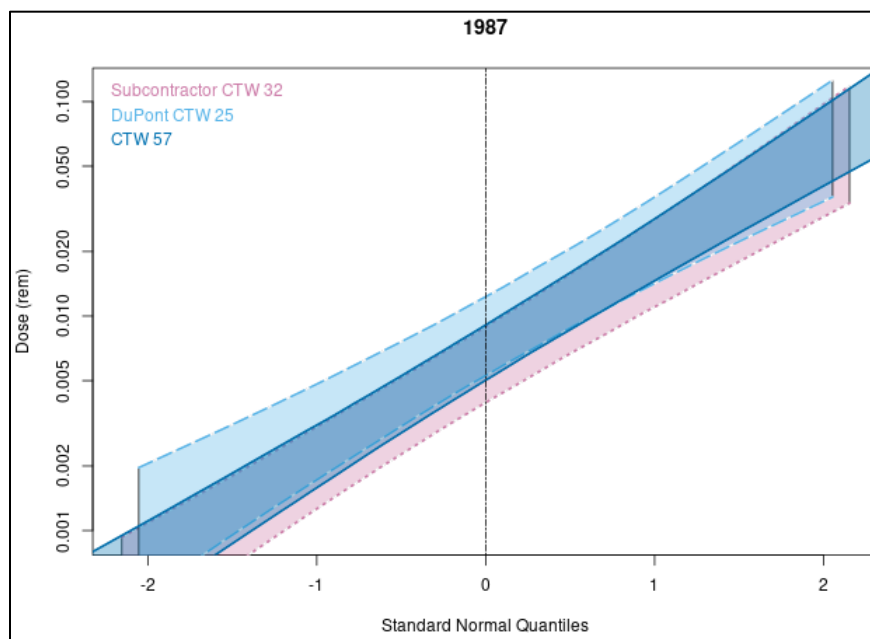
**Figure 5. Density plots of the doses at the vertical dashed line in Figure 4 (the 50th percentile doses) for all workers, CTWs, and nonCTWs for 1987. The vertical dashed lines are the point estimates of the 50th percentiles from the respective co-exposure models.**

Again, while not a formal statistical test, the extent to which the curves in Figure 5 overlap is a clear indication that the three distributions are essentially the same. Stratifying the co-exposure model in this case leads to less precise estimates of dose. This principle is illustrated further when the 57 CTWs are stratified into 32 Subcontractor (Sub) CTWs and 25 DuPont CTWs:

- Figure 6 shows the comparison of confidence bands for Subcontractor CTWs, DuPont CTWs, and all CTWs. The CTW confidence band is narrower than the confidence bands for the substrata.

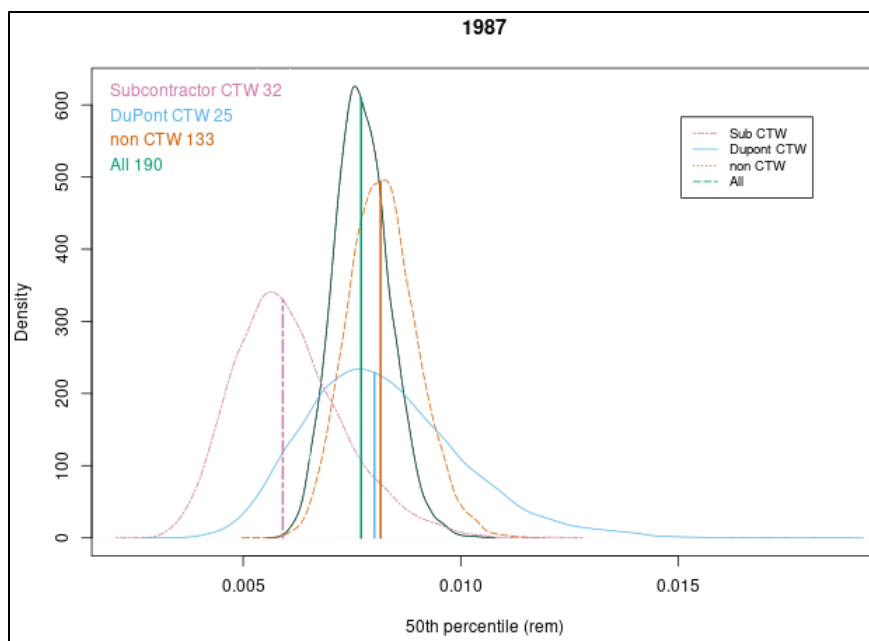
- The density plots of the 50th percentiles in Figure 7 for all workers, Subcontractor CTWs, DuPont CTWs, and nonCTWs show no significant difference in the distributions, but the widths of the two substratified CTW distributions are inflated, resulting in greater uncertainty in doses predicted from those co-exposure models.

The plots in this section are summarized in Table 1. Plots for CTWs, Subcontractor CTWs, and DuPont CTWs for 1972 to 1990 can be found in Appendix A. Plots for all groups and all years are also available [ORAUT 2021a, 2021b]. Tabled values (like the ones in Table 1) for all years can be found in Appendix B.



**Figure 6. Confidence bands for CTWs, Subcontractor CTWs, and DuPont CTWs for 1987. The vertical dashed line is the median (50th percentile) of the distributions.**





**Figure 7. Density plots of the 50th percentile dose (the vertical dashed line in Figure 4) for all workers, DuPont CTWs, Subcontractor CTWs, and nonCTWs for 1987. The vertical dashed lines are the point estimates of the 50th percentiles.**

**Table 1. Point estimates and 95% confidence intervals for geometric mean, 84th percentile, and 95th percentile for each group of workers in 1987.**

Group	GM Estimate (95% CI) <sup>a</sup>	84th Estimate (95% CI)	95th Estimate (95% CI)
Sub CTW	0.0059 (0.0040, 0.0089)	0.0184 (0.0110, 0.0282)	0.0382 (0.0207, 0.0624)
DuPont CTW	0.0080 (0.0053, 0.0123)	0.0231 (0.0142, 0.0359)	0.0457 (0.0253, 0.0768)
CTW	0.0068 (0.0050, 0.0091)	0.0209 (0.0146, 0.0284)	0.0432 (0.0283, 0.0616)
nonCTW	0.0082 (0.0067, 0.0099)	0.0249 (0.0196, 0.0313)	0.0510 (0.0381, 0.0669)
All Workers	0.0077 (0.0066, 0.0091)	0.0237 (0.0194, 0.0287)	0.0490 (0.0386, 0.0612)

a. CI = confidence interval.

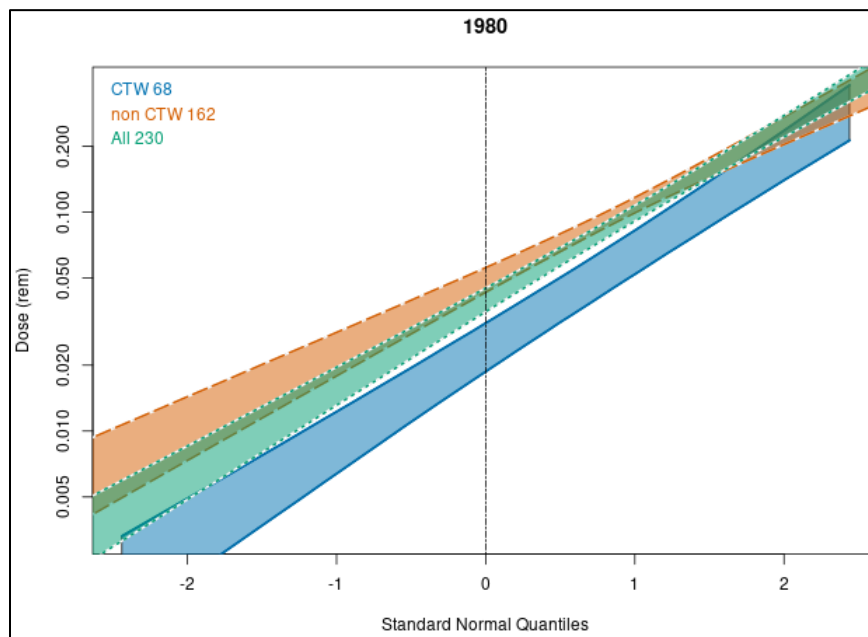
The point to take away from this example is that poststratifying a simple random sample (e.g., a NOCTS sample) will, in general, result in increased uncertainty in the resulting co-exposure models compared with co-exposure models derived from properly stratified samples. Co-exposure models derived from prestratified or poststratified samples, when there are in reality no significant differences between the distributions of the doses in the strata, will result in co-

exposure models that are inherently more uncertain than the co-exposure model derived from unstratified data.

### **UNCERTAINTY ANALYSIS OF TRITIUM CO-EXPOSURE MODELS FOR 1980**

The data from 1987 illustrated the case where the co-exposure model probably should not have been stratified. The data from 1980 is an example where stratification may be warranted. The confidence bands for the CTW, nonCTW, and all worker co-exposure models are shown together in Figure 8, which is analogous to Figure 4 for the 1987 models. One can conclude from this plot that:

- The three 95% confidence bands do not overlap in the entire range of the observed data, especially around the 50th percentile.
- The confidence band for the co-exposure model constructed from all 230 doses is narrower than the confidence bands for the stratified co-exposure models.

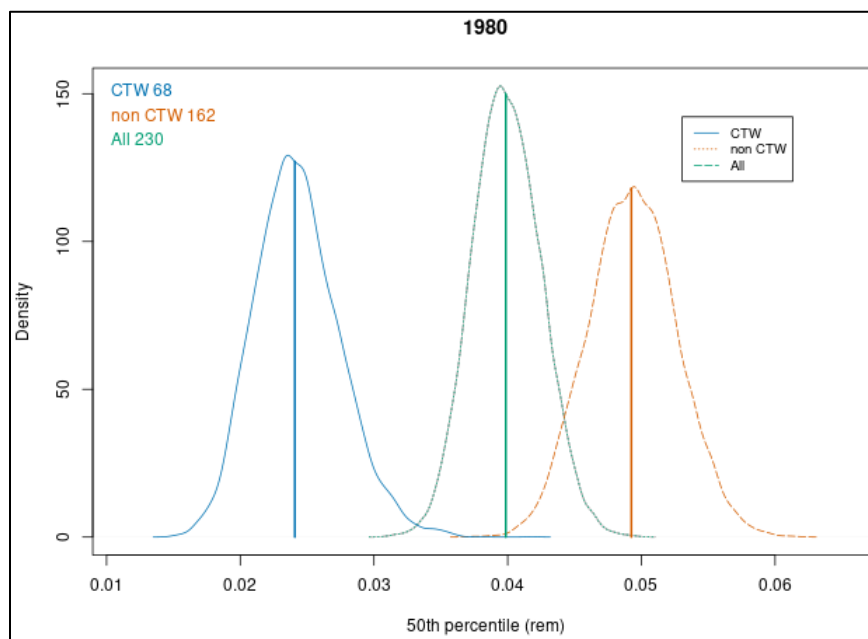


**Figure 8. Confidence bands for all workers, CTWs, and nonCTWs for 1980.**

This last conclusion might be somewhat confusing at first glance, because we expected the stratified co-exposure models to be more precise (i.e., have narrower bands). However, this is strictly true only when the study sample is designed to be stratified before the sample is collected (prestratification). For these NOCTS data, the sample was collected and poststratified into the subgroups, a problem that was discussed in the previous section. Another way to look at this is to think about the situation where the study sample was stratified by design before the sample was collected, with 230 CTWs being sampled (instead of 68) and 230 nonCTWs being sampled

(instead of 162). With those sample sizes, the stratified co-exposure models would most likely be more precise than the combined co-exposure model having 230 doses. As stated before, to be truly effective, stratified samples should be collected by design rather than stratified after the sample is collected.

The large difference in the CTW and nonCTW co-exposure models is reflected in the probability density curves for the 50th percentile in Figure 9. These are for tritium doses in 1980 and are analogous to those given in Figure 5 for tritium doses in 1987. This clearly shows that, in contrast to 1987, the stratified co-exposure models for CTWs and nonCTWs in 1980 are sufficiently different to perhaps warrant stratification. The plots in this section are summarized in Table 2.



**Figure 9. Density plots of the 50th percentile dose (the vertical dashed line in Figure 8) for all workers, CTWs, and nonCTWs for 1980. The vertical dashed lines are the point estimates of the 50th percentiles.**

**Table 2. Point estimates and 95% confidence intervals for geometric mean, 84th percentile, and 95th percentile for groups of workers in 1980.**

Group	GM Estimate (95% CI) <sup>a</sup>	84 <sup>th</sup> Estimate (95% CI)	95 <sup>th</sup> Estimate (95% CI)
CTW	0.0241 (0.0187, 0.0311)	0.0668 (0.0521, 0.0827)	0.1284 (0.0990, 0.1615)
nonCTW	0.0493 (0.0431, 0.0558)	0.1079 (0.0994, 0.1168)	0.1787 (0.1595, 0.2003)
All Workers	0.0399 (0.0351, 0.0450)	0.0993 (0.0911, 0.1075)	0.1787 (0.1624, 0.1967)

a. CI = confidence interval.

## SUMMARY

In summary:

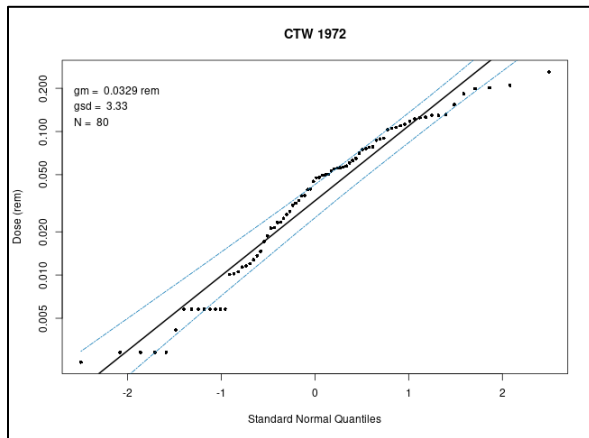
- Stratification of the study sample into subgroups for the creation of stratified co-exposure models is warranted when the distribution of the doses in the subgroups are significantly different. Stratification in this case will lead to co-exposure models with lower uncertainty, if the stratified samples are collected by design and not by poststratification.
- Stratification of the study sample into subgroups when there are in fact no significant differences in the distribution of doses in the subgroups will result in co-exposure models with inflated uncertainties, which is undesirable.
- Consideration of the uncertainty in co-exposure models is required to determine if predefined strata are indeed sufficiently different to warrant stratification.
- Note that it is not appropriate to test for significant differences between strata that are proposed after the sample is collected and analyzed, i.e., one should not use the same data to propose strata and test these proposed strata for differences.

The co-exposure model uncertainty analyses mentioned in the third bullet are relatively straightforward in simple cases like for tritium dose, which is why it was chosen to use as an example here. However, such analyses for materials like plutonium are considerably more difficult because of the presence of censored data and the complexity of the procedure (e.g., imputation of censored data, time-weighted one person–one statistic (TWOPOS), and intake modeling) used to go from bioassay data to dose (or intake). Perhaps a larger obstacle to performing uncertainty analyses on co-exposure models is the use of claimant-favorable assumptions in the development of those models that intentionally bias the model (i.e., how does one calculate the uncertainty in a model that is known to be biased by an undetermined amount?).

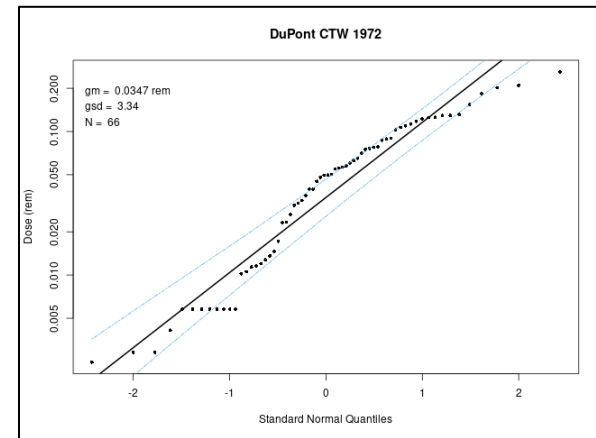
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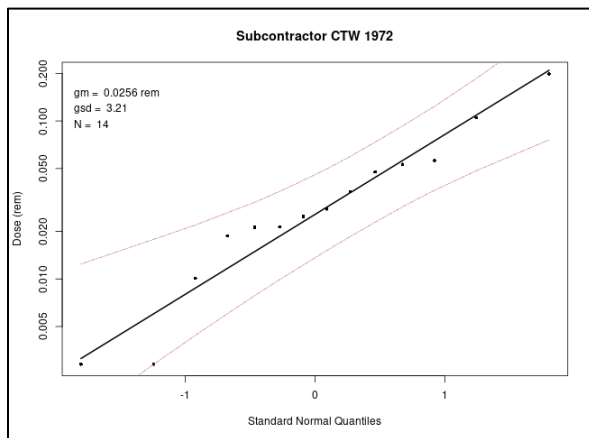
**APPENDIX A: Plots for CTWs, Subcontractor CTWs, and DuPont CTWs for 1972-1990**



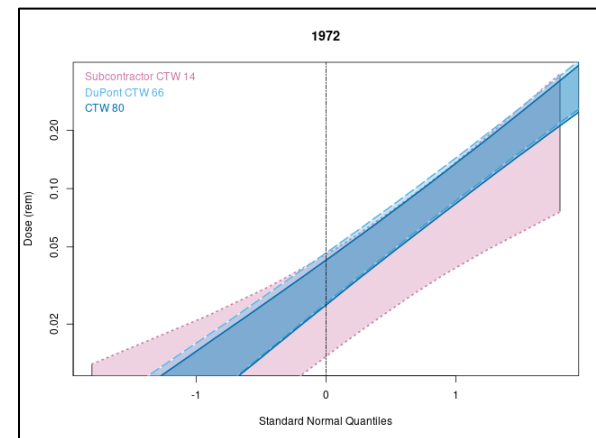
**Figure A1. QQ plot for CTW 1972.**



**Figure A3: QQ plot for DuPont CTW 1972.**



**Figure A2. QQ plot for Sub CTW 1972.**



**Figure A4: Band plot for 1972.**

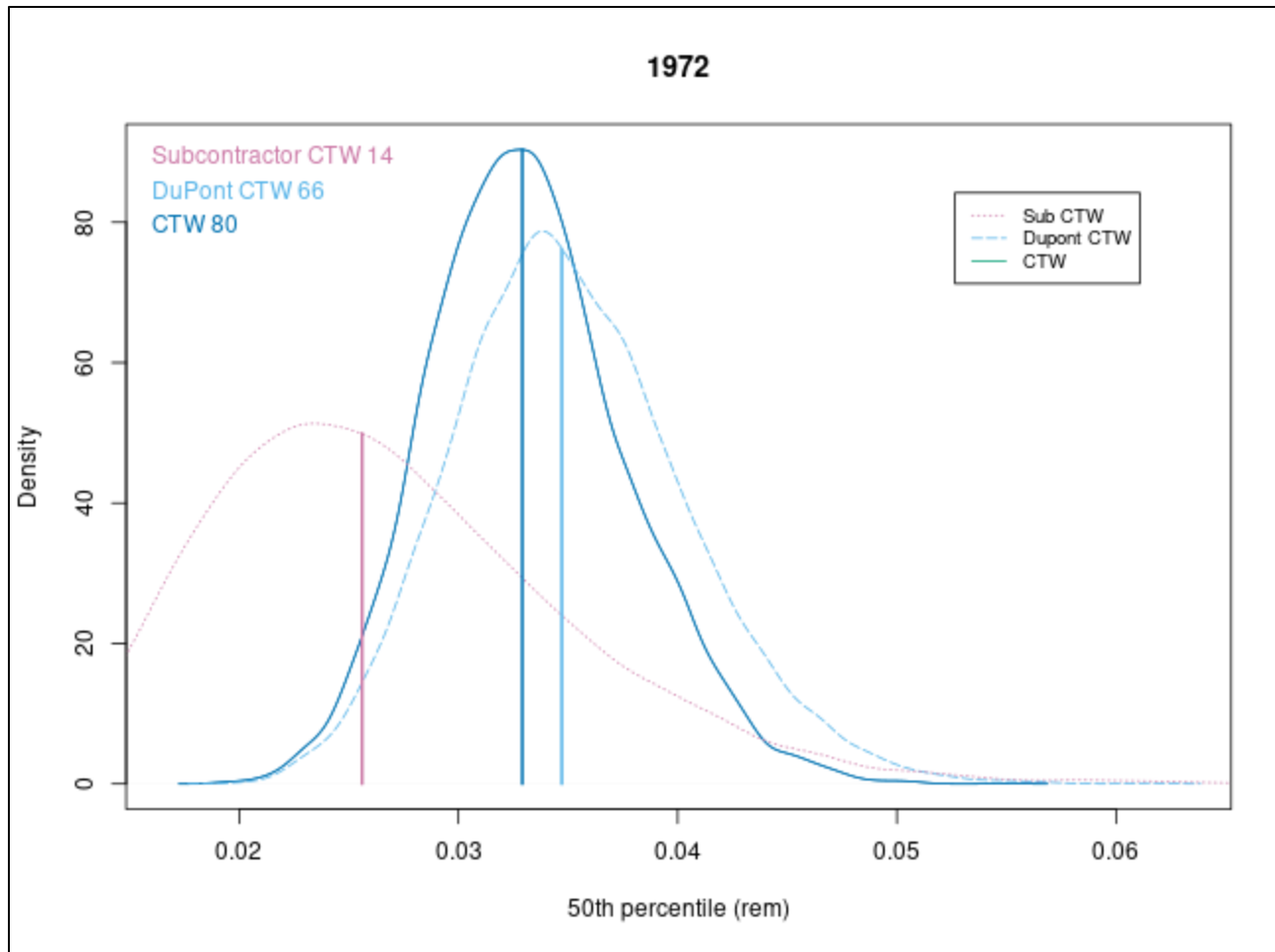


Figure A5. Density plot for 1972.

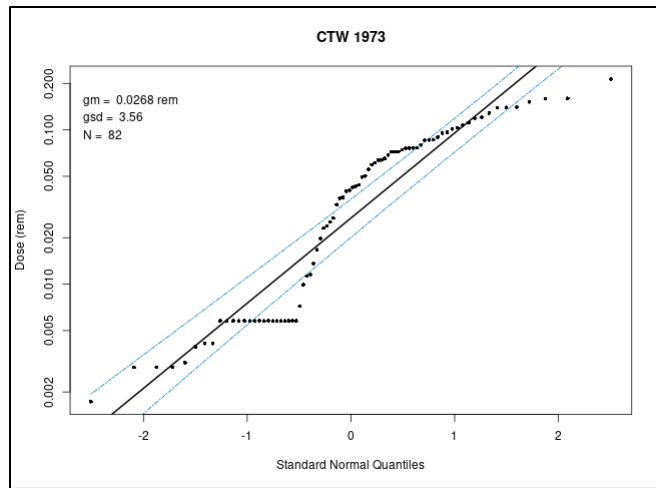


Figure A6. QQ plot for CTW 1973.

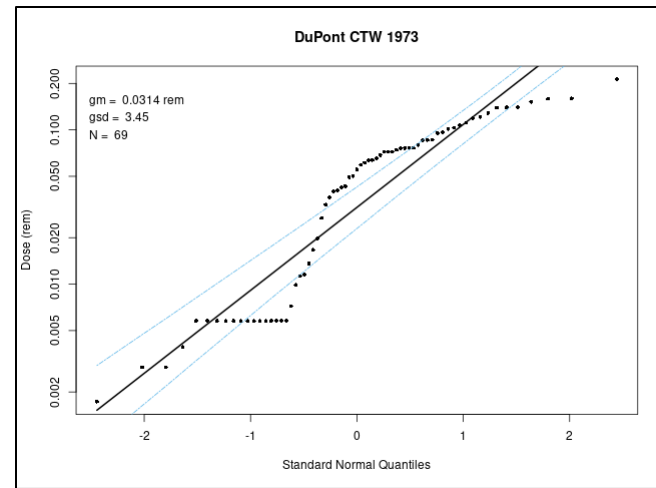


Figure A8. QQ plot for DuPont CTW 1973.

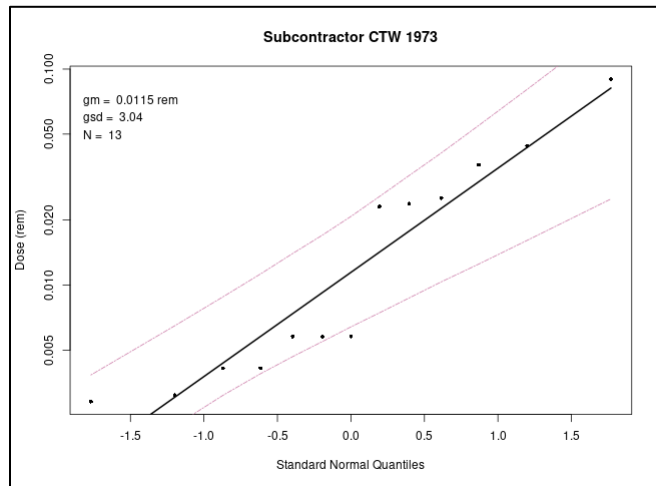


Figure A7. QQ plot for Sub CTW 1973.

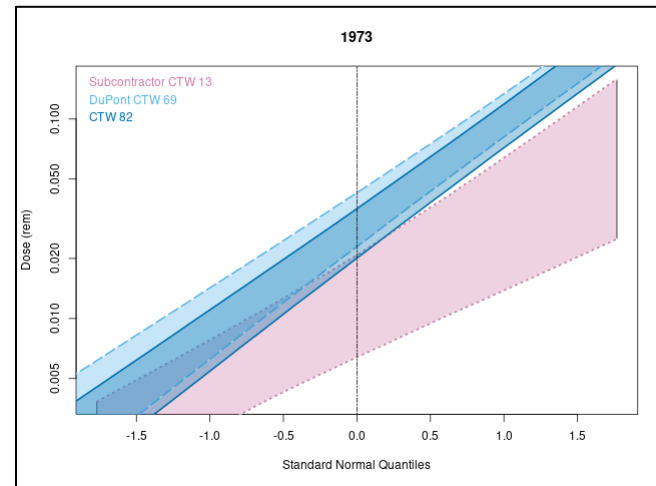


Figure A9. Band plot for 1973.



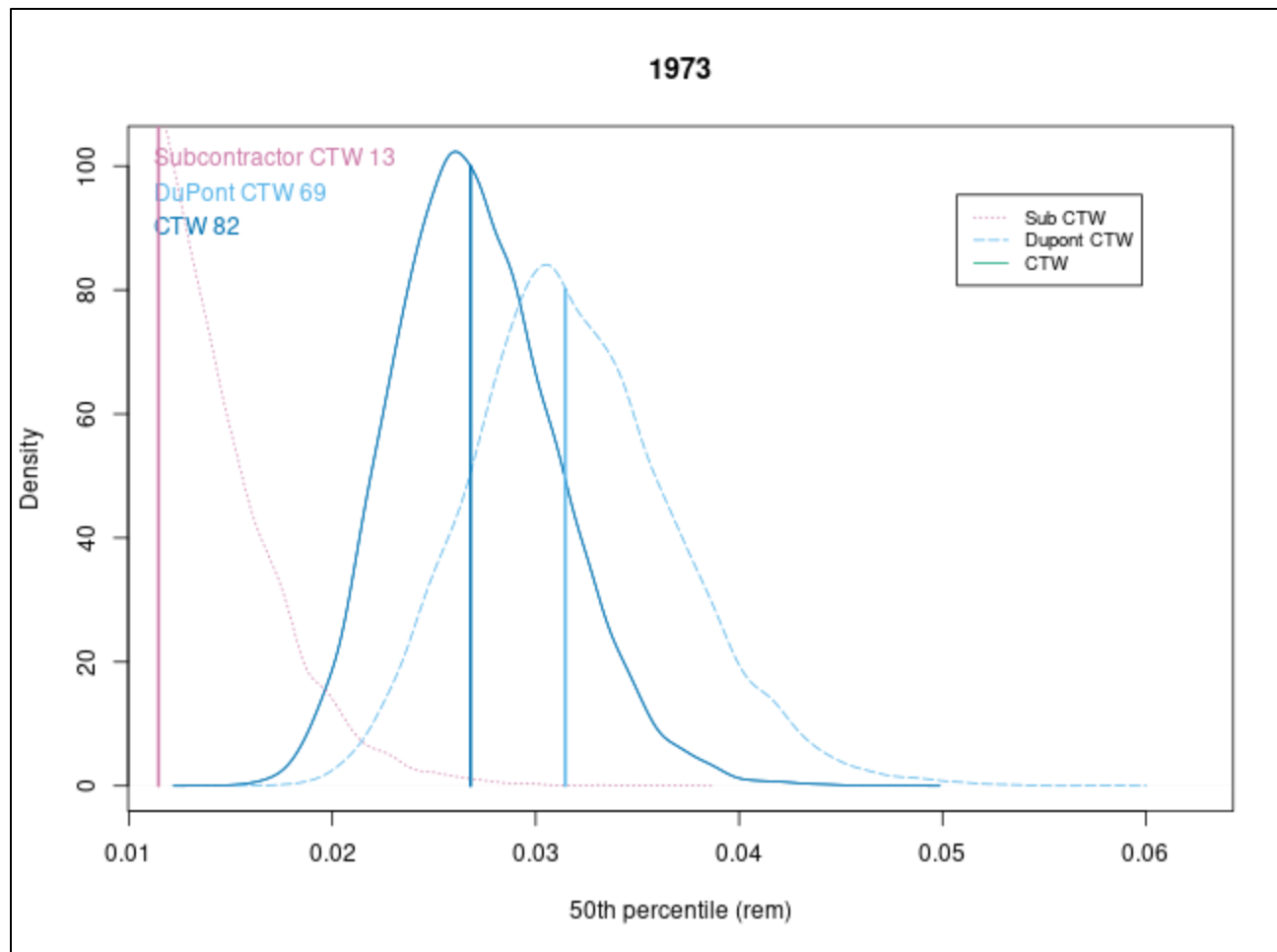


Figure A10. Density plot for 1973.

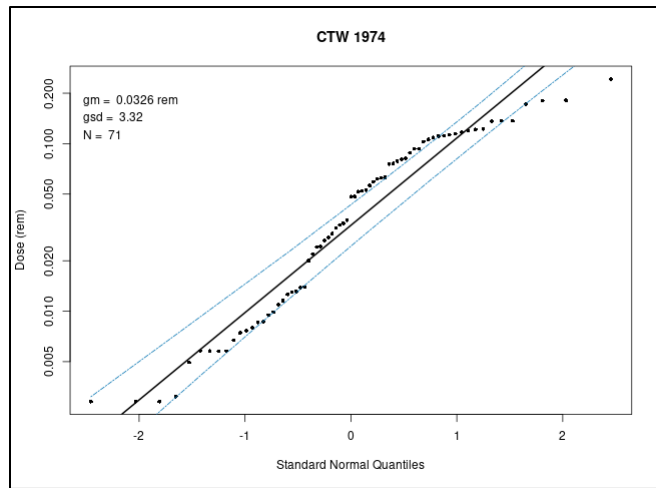


Figure A11. QQ plot for CTW 1974.

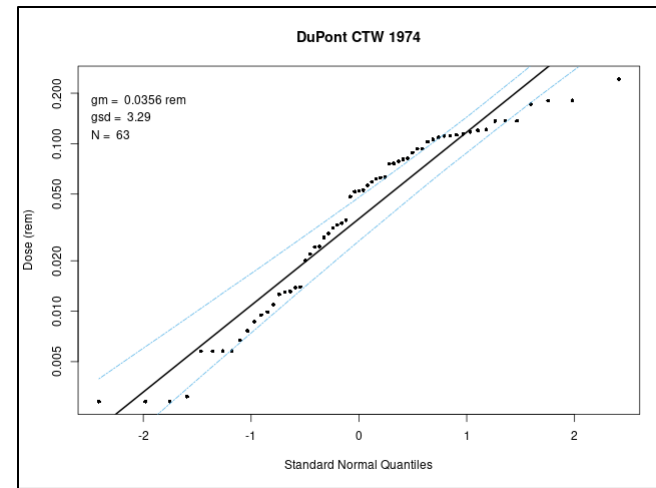


Figure A13. QQ plot for DuPont CTW 1974.

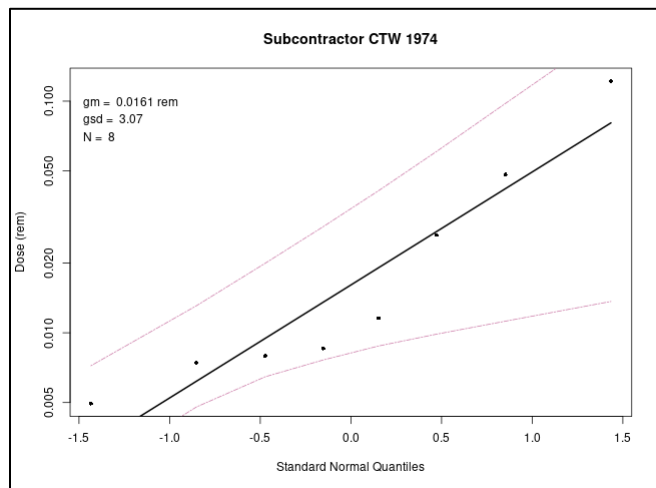


Figure A12. QQ plot for Sub CTW 1974.

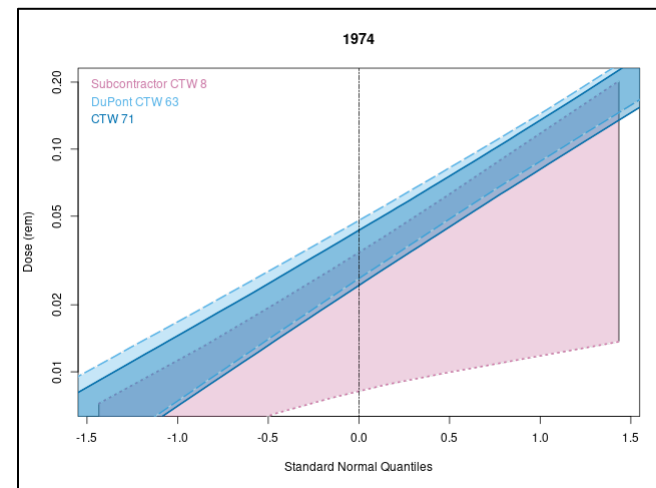


Figure A14. Band plot for 1974.

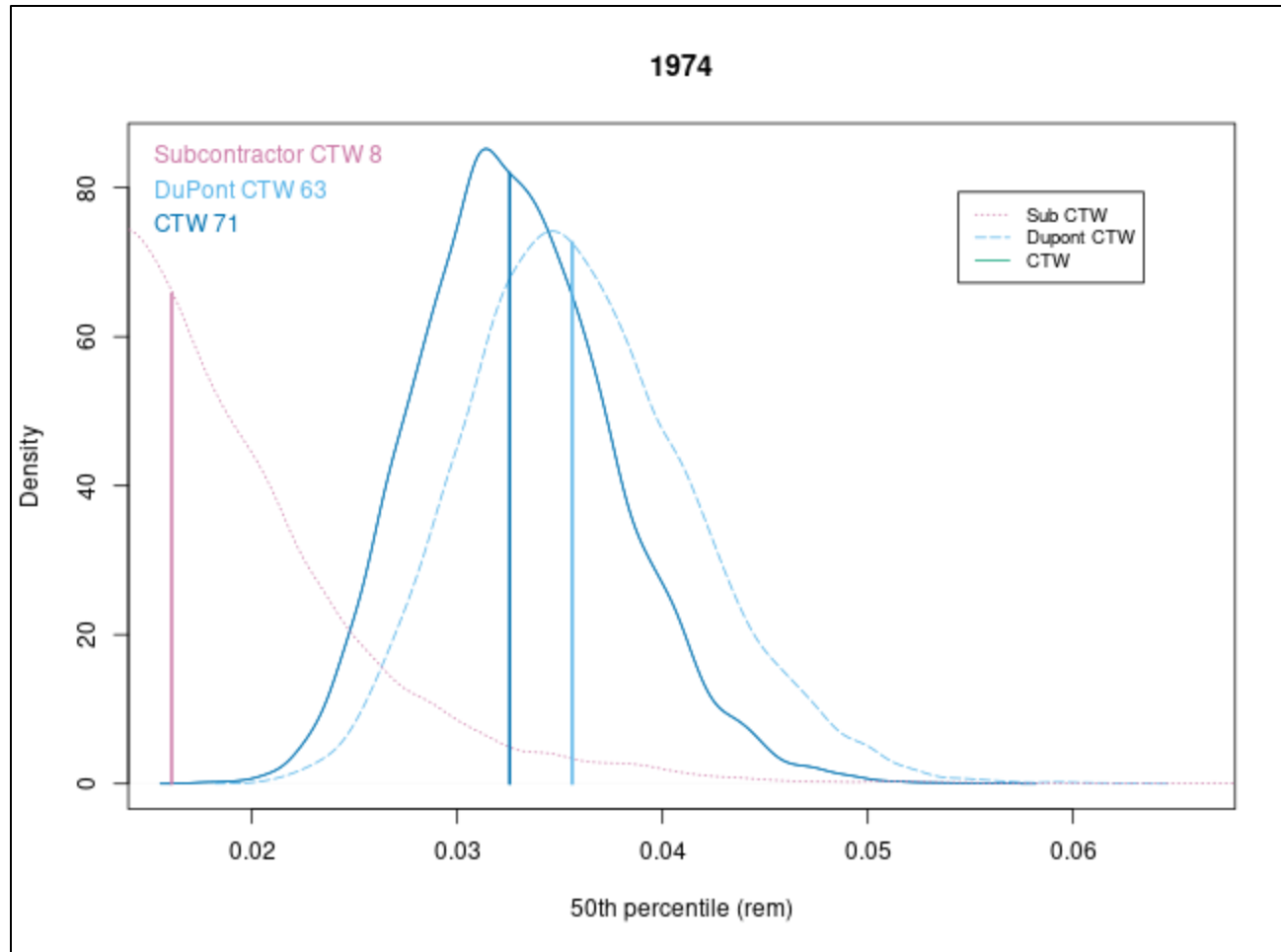


Figure A15. Density plot for 1974.

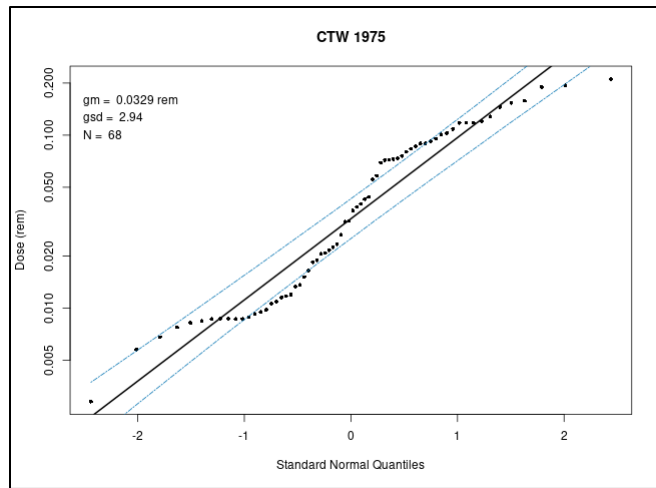


Figure A16. QQ plot for CTW 1975.

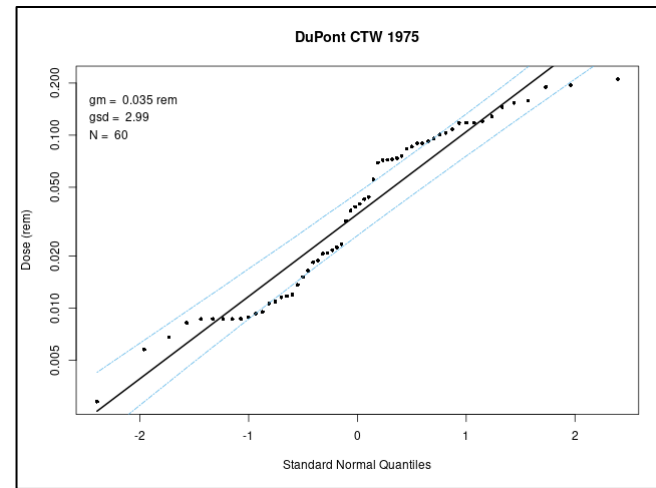


Figure A18. QQ plot for DuPont CTW 1975.

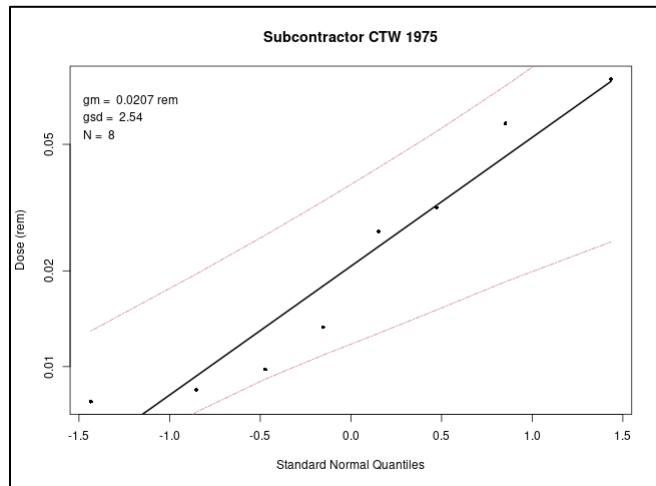


Figure A17. QQ plot for Sub CTW 1975.

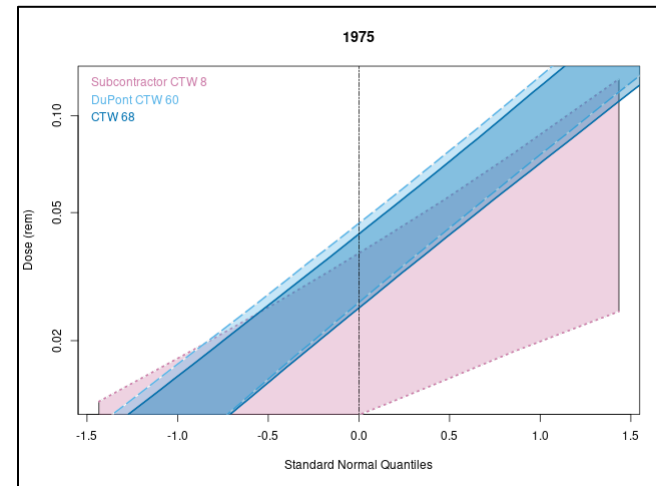


Figure A19. Band plot for 1975.

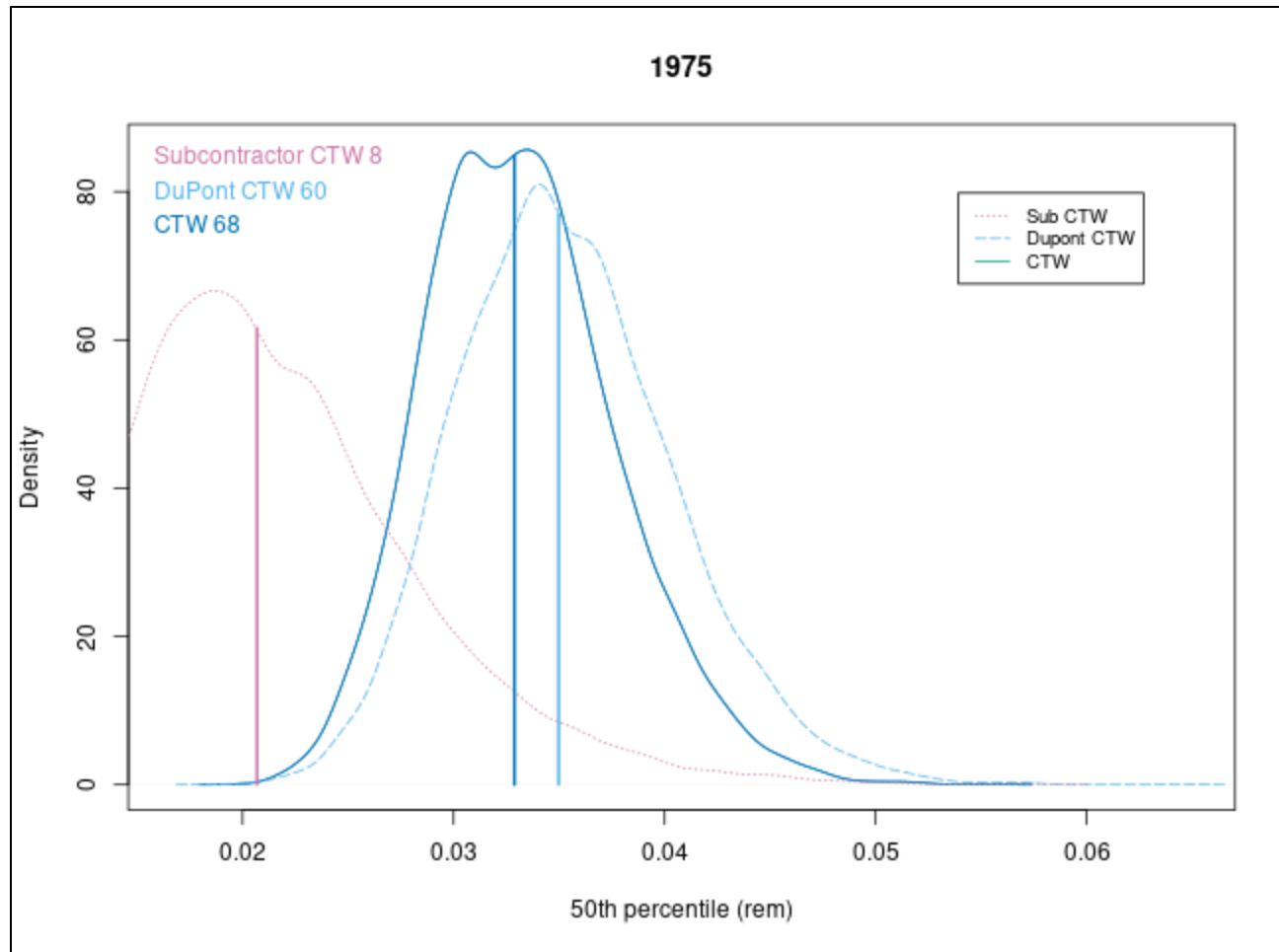


Figure A20. Density plot for 1975.

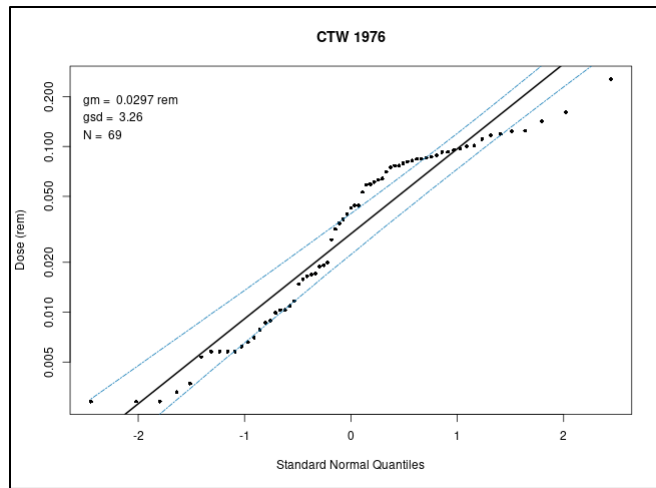


Figure A21. QQ plot for CTW 1976.

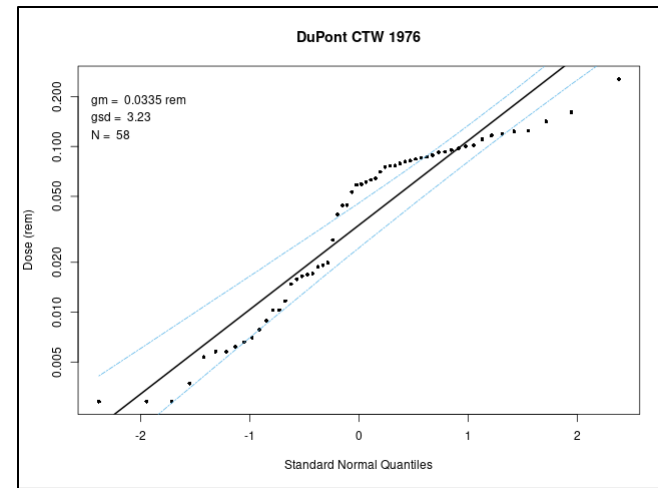


Figure A23. QQ plot for DuPont CTW 1976.

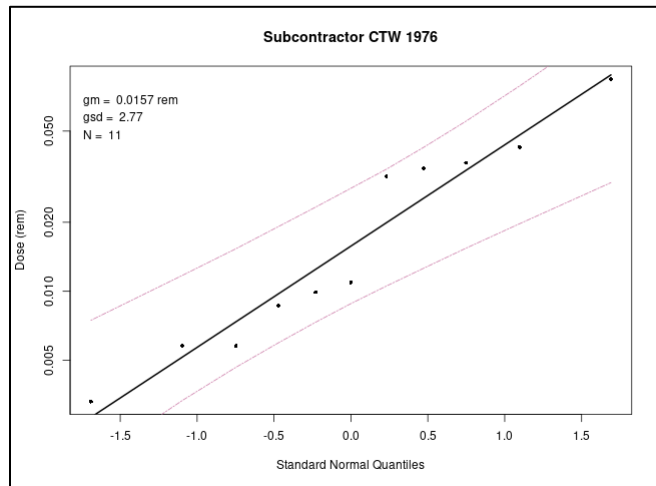


Figure A22. QQ plot for Sub CTW 1976.

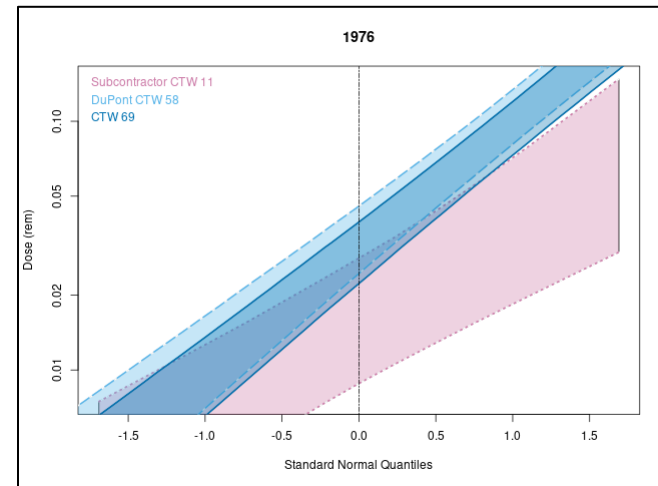


Figure A24. Band plot for 1976.

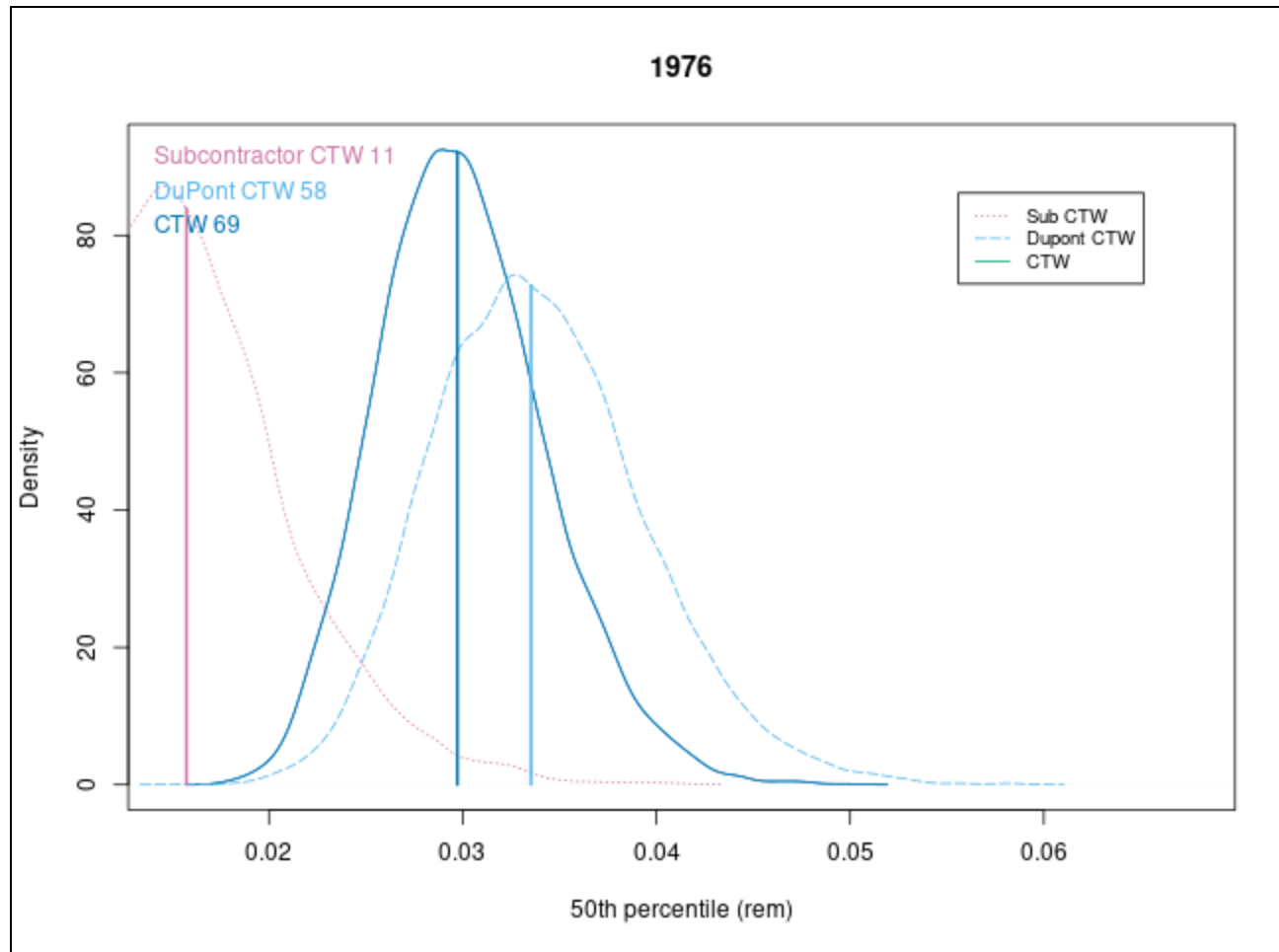


Figure A25. Density plot for 1976.

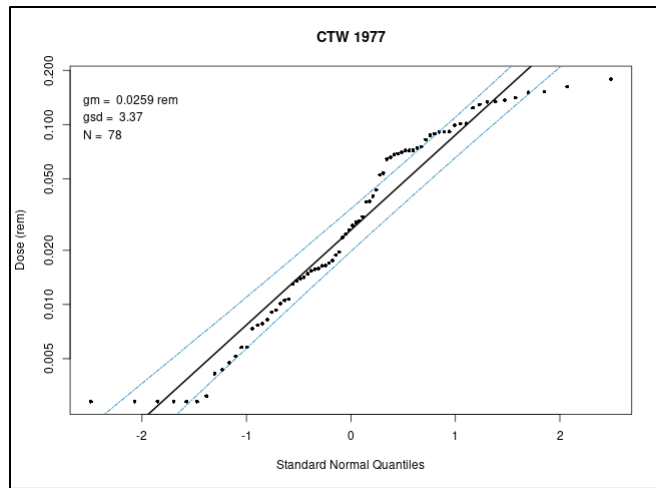


Figure A26. QQ plot for CTW 1977.

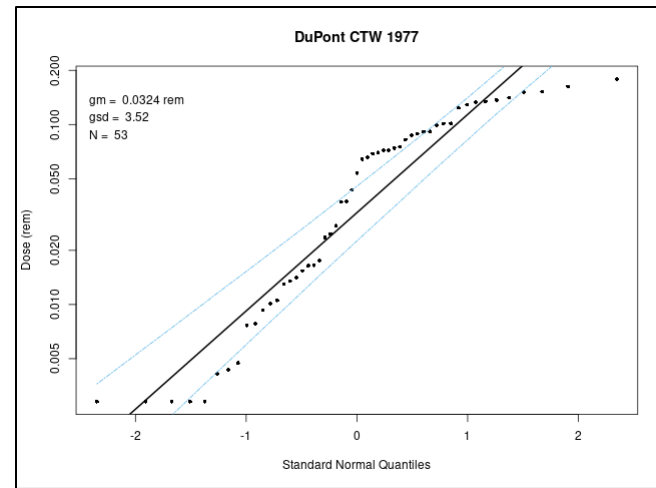


Figure A28. QQ plot for DuPont CTW 1977.

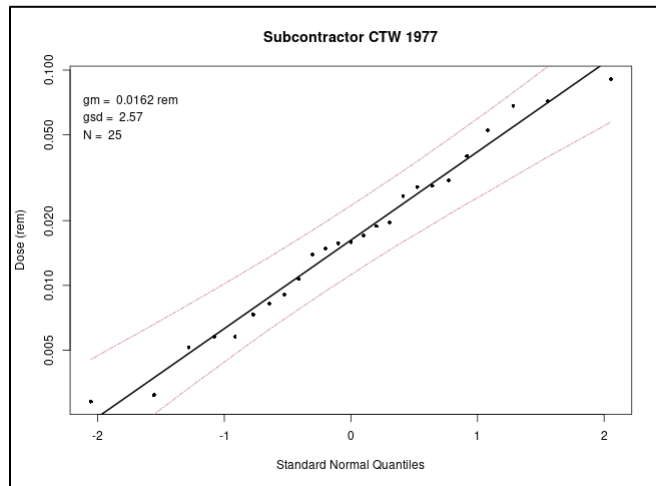


Figure A27. QQ plot for Sub CTW 1977.

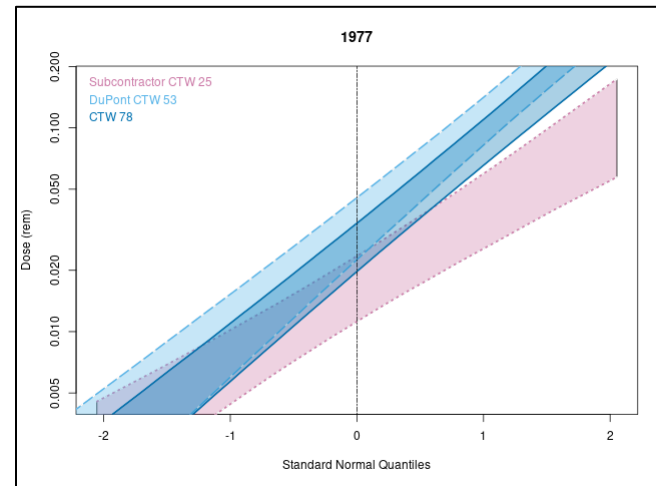


Figure A29. Band plot for 1977.



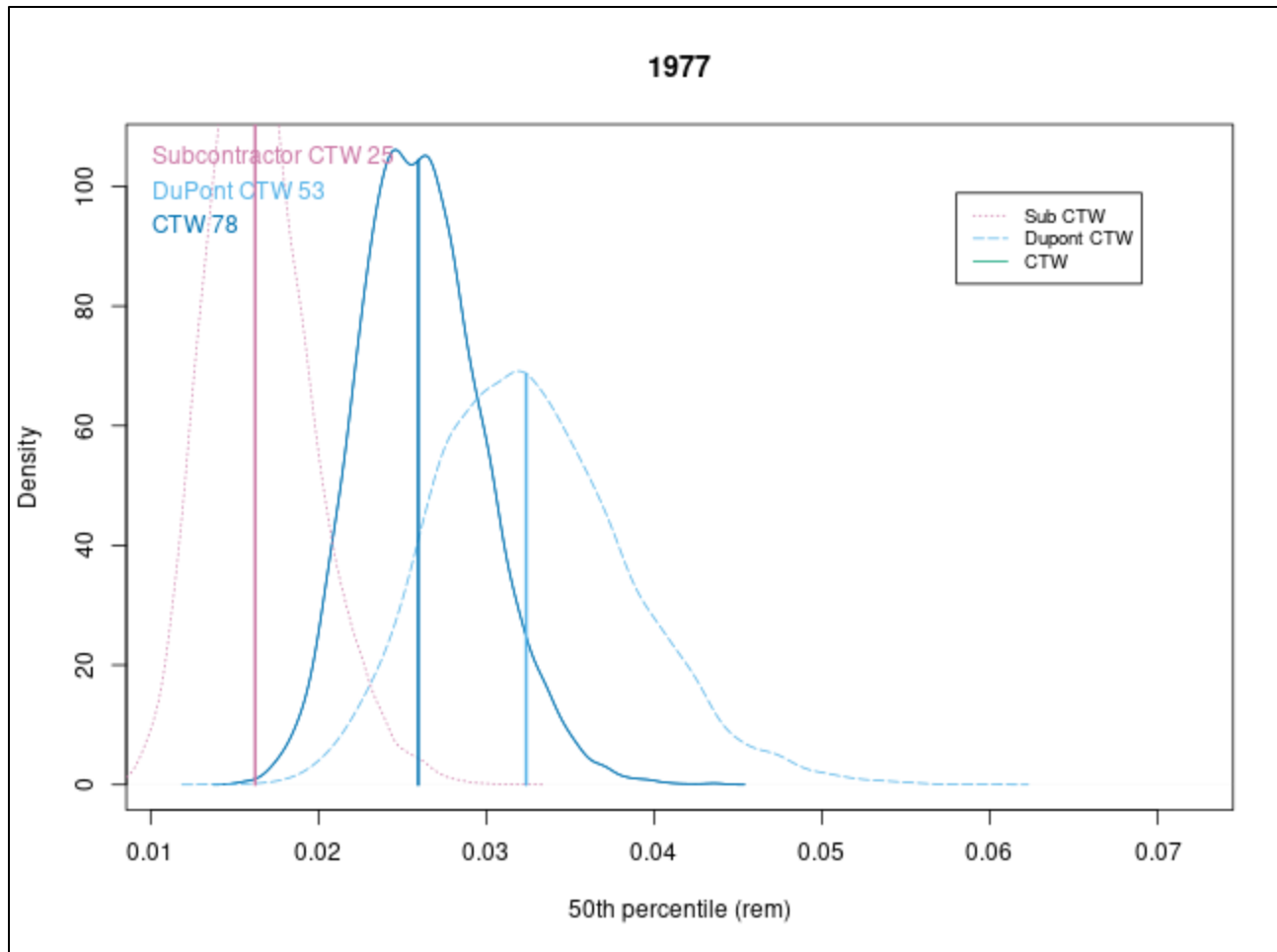


Figure A30. Density plot for 1977.

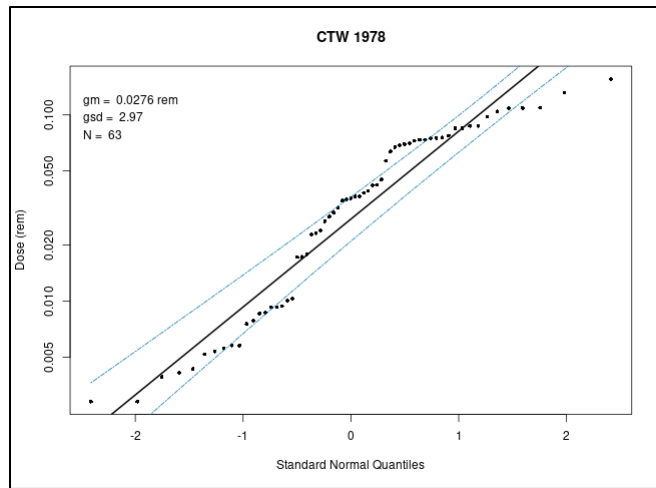


Figure A31. QQ plot for CTW 1978.

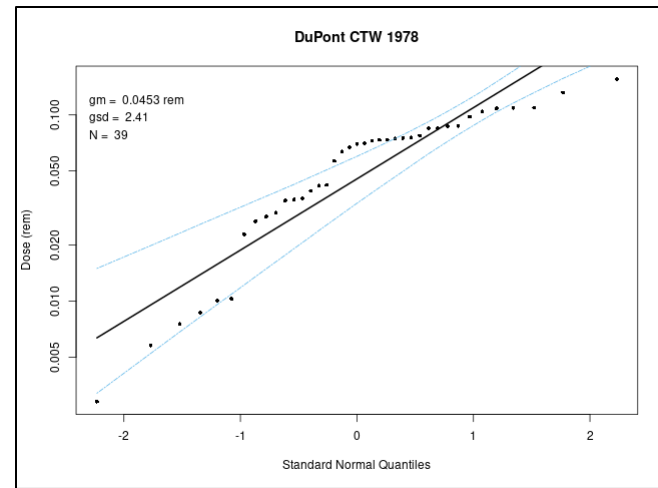


Figure A33. QQ plot for DuPont CTW 1978.

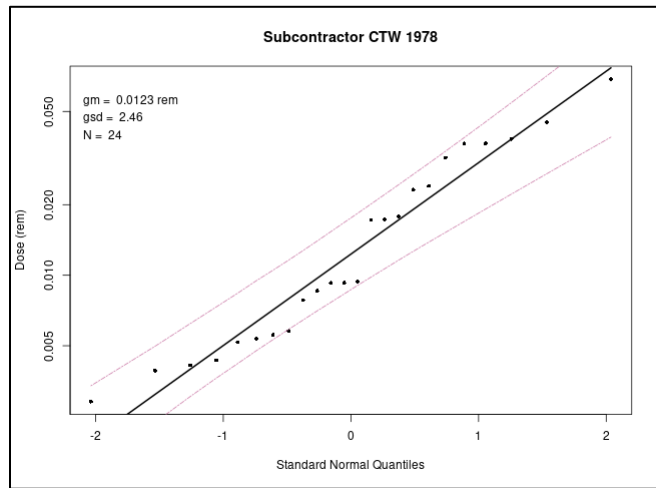


Figure A32. QQ plot for Sub CTW 1978.

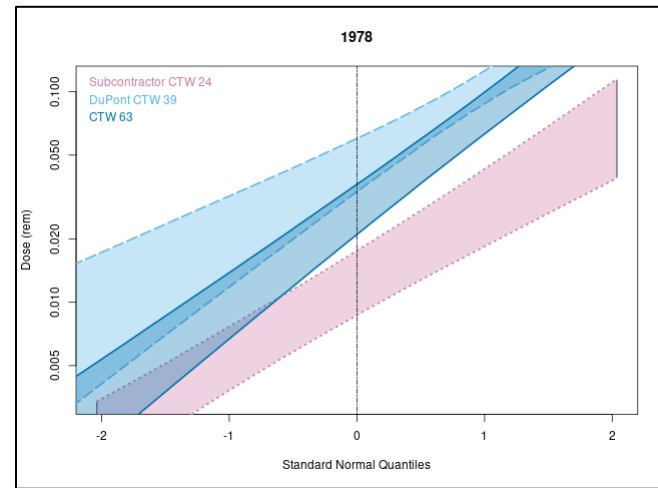


Figure A34. Band plot for 1978.

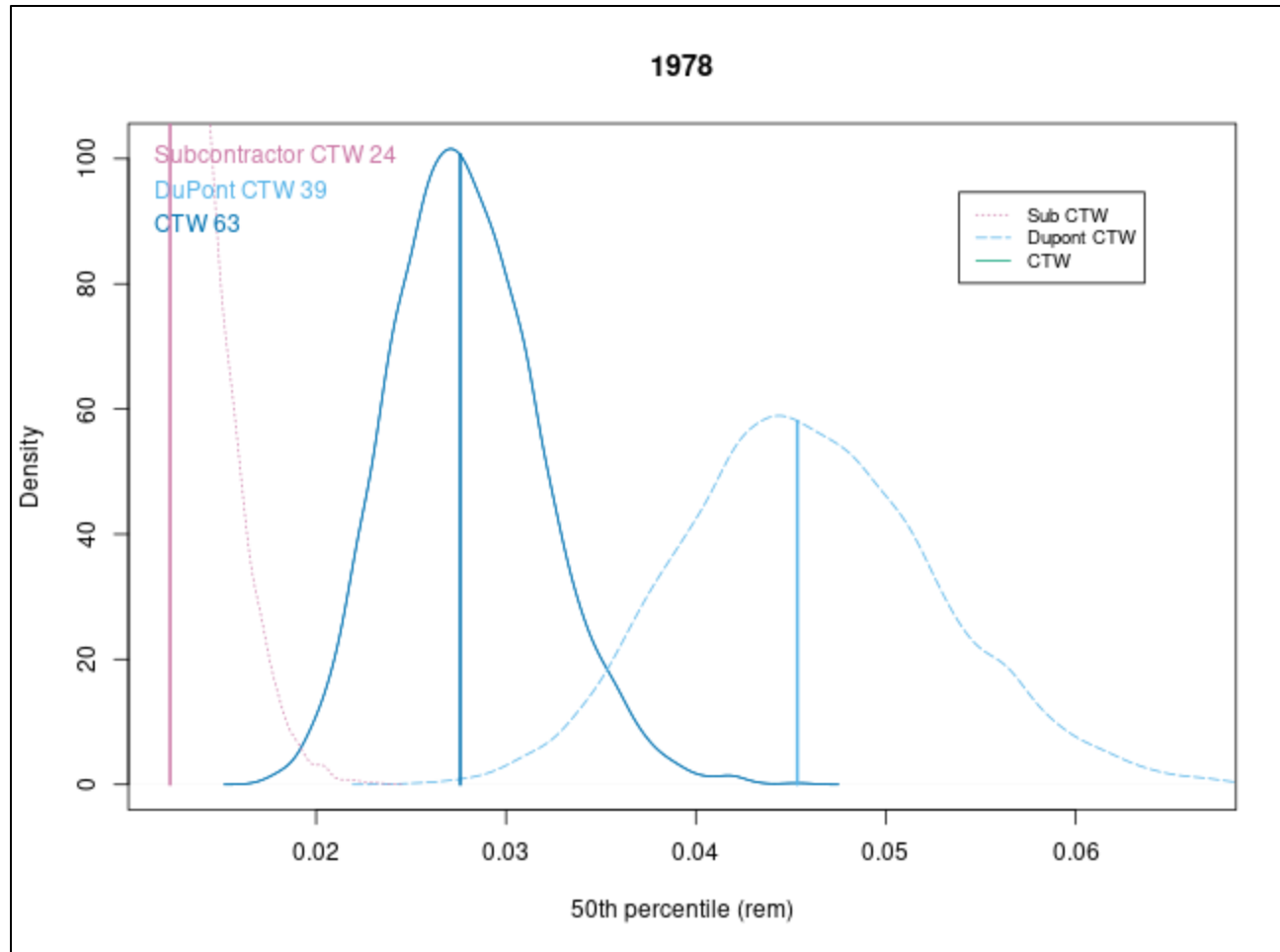


Figure A35. Density plot for 1978.

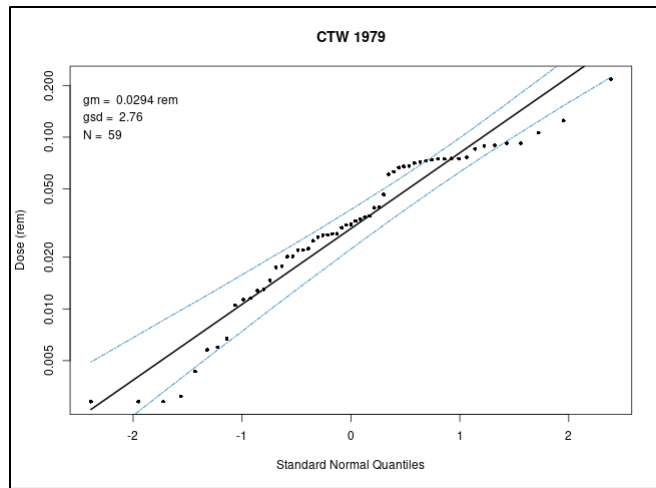


Figure A36. QQ plot for CTW 1979.

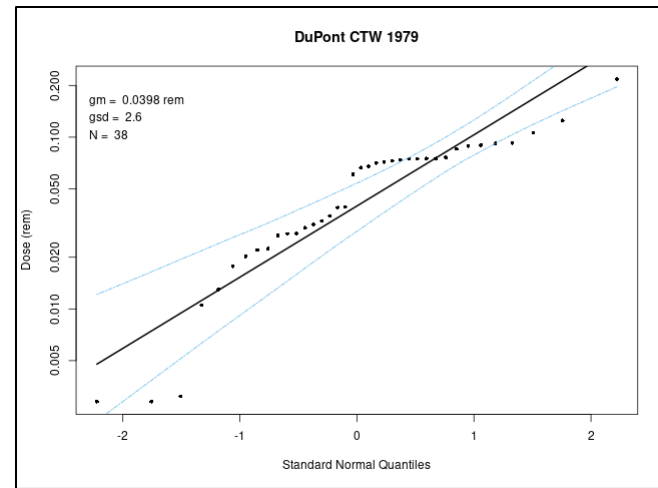


Figure A38. QQ plot for DuPont CTW 1979.

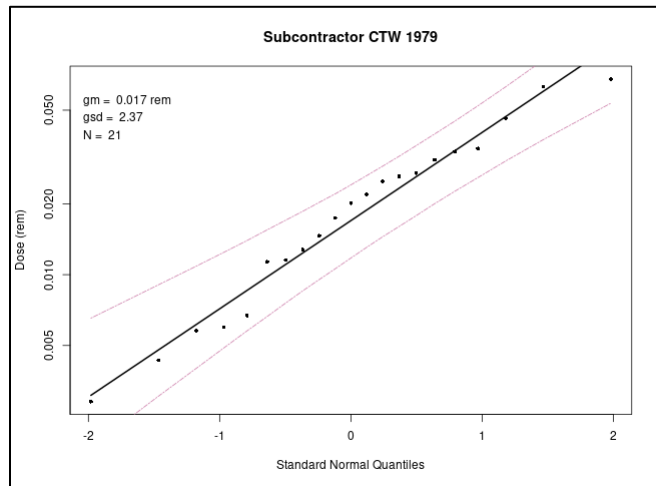


Figure A37. QQ plot for Sub CTW 1979.

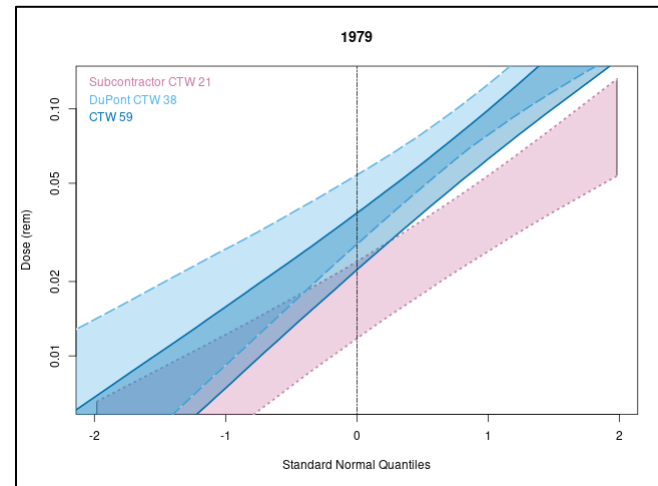


Figure A39. Band plot for 1979.

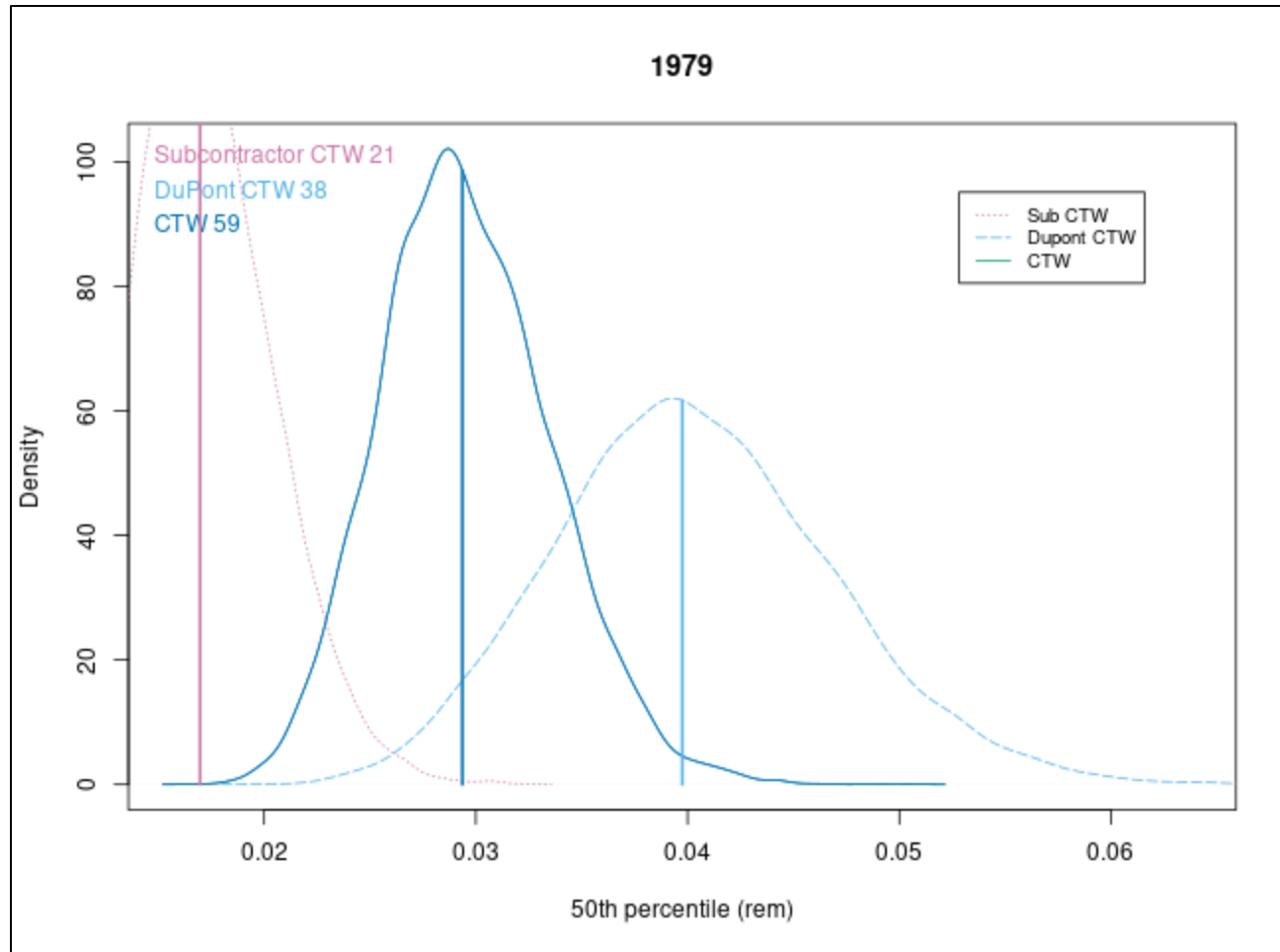


Figure A40. Density plot for 1979.

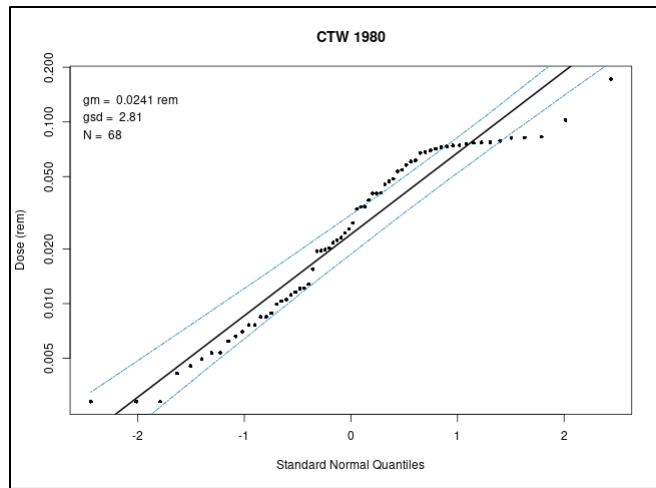


Figure A41. QQ plot for CTW 1980.

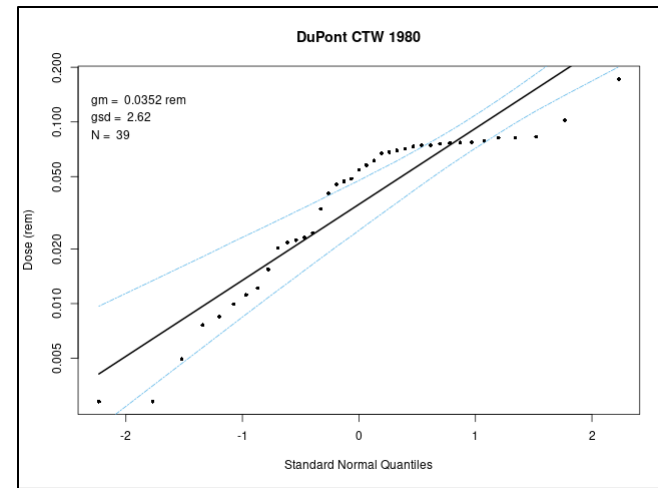


Figure A43. QQ plot for DuPont CTW 1980.

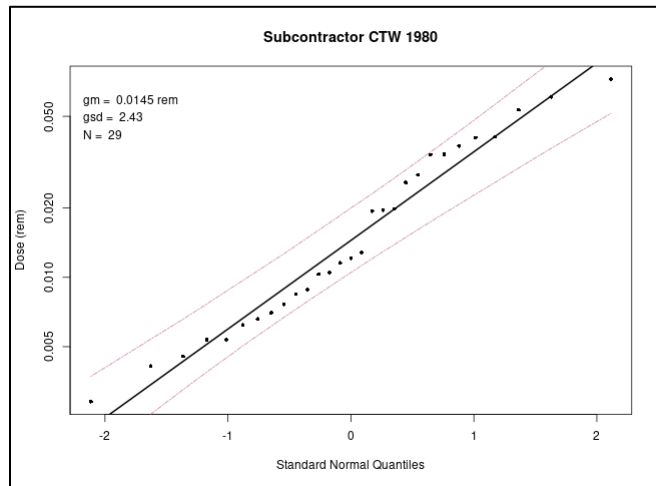


Figure A42. QQ plot for Sub CTW 1980.

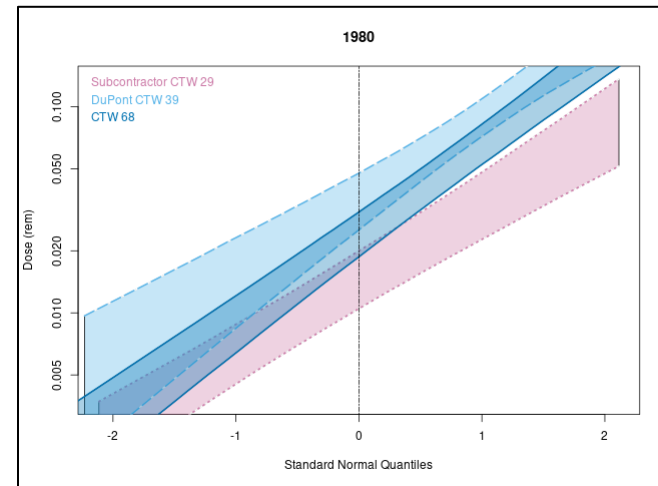


Figure A44. Band plot for 1980.

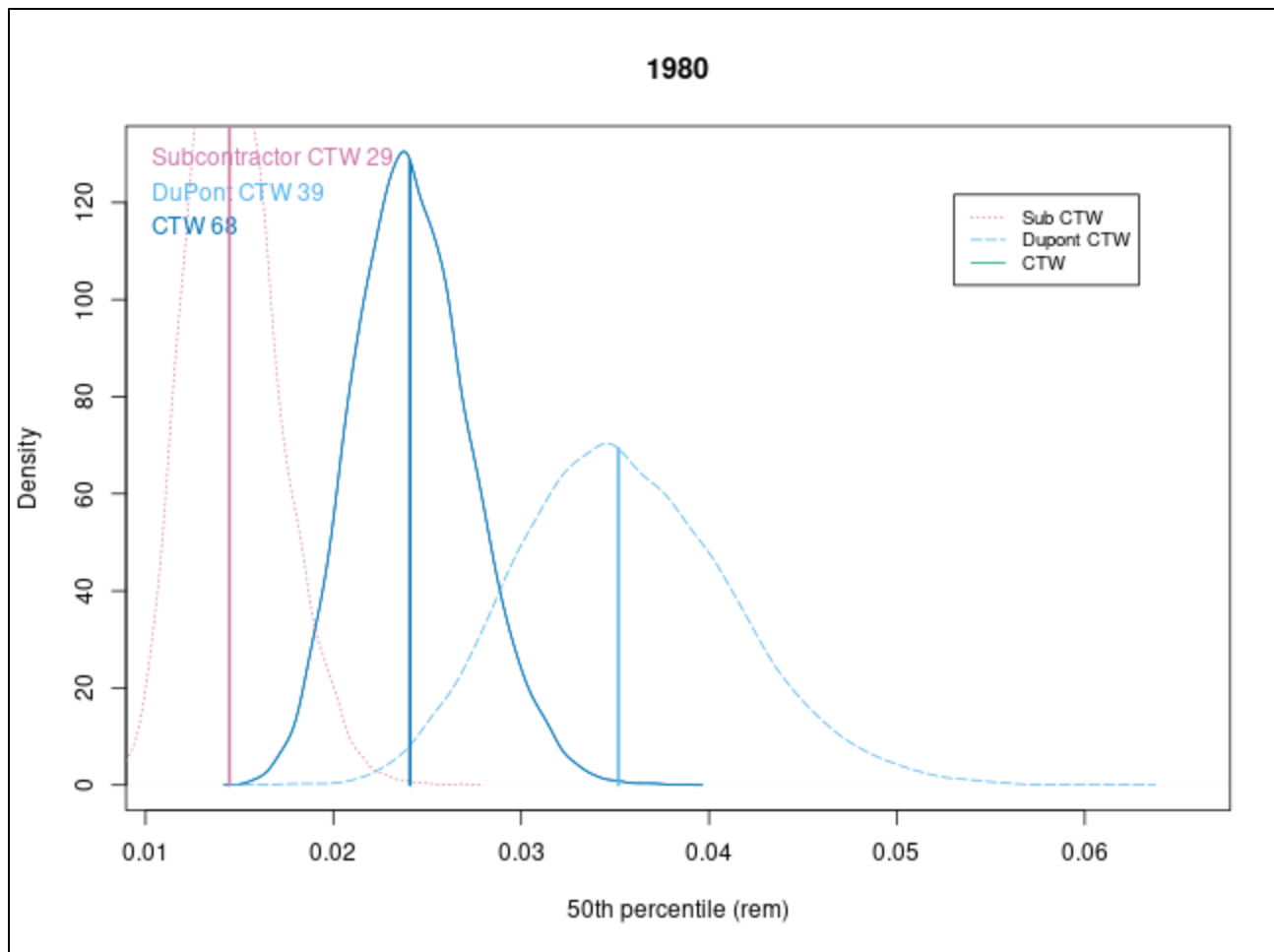


Figure A45. Density plot for 1980.

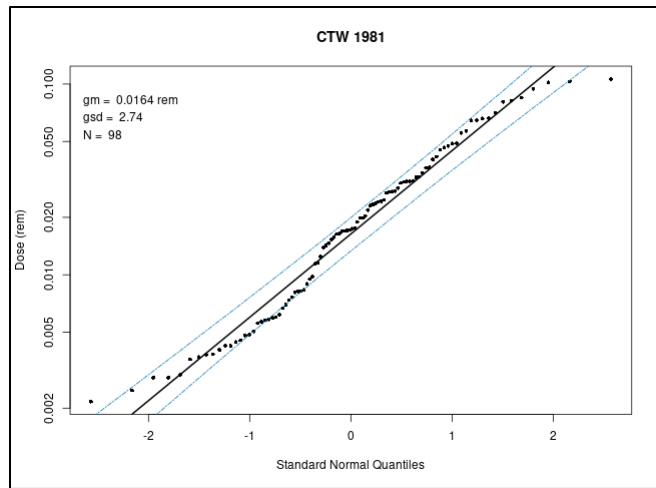


Figure A46. QQ plot for CTW 1981.

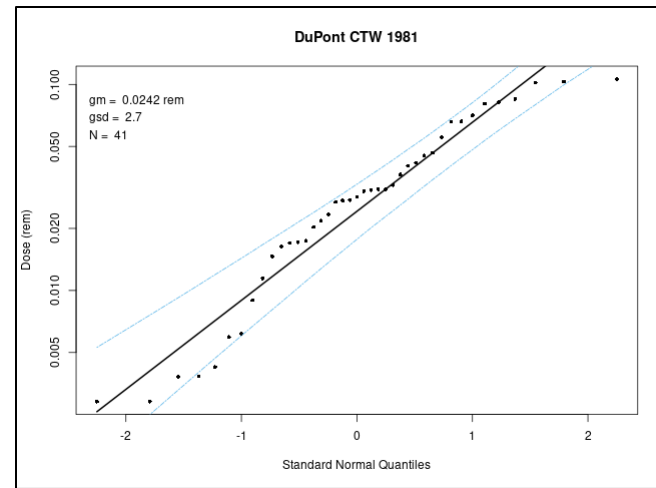


Figure A48. QQ plot for DuPont CTW 1981.

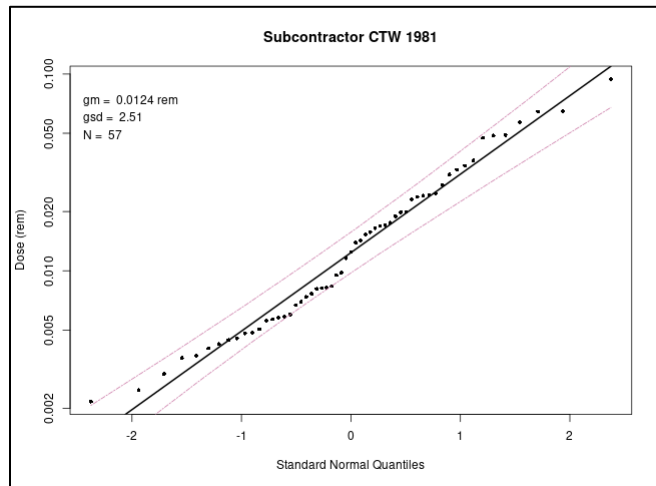


Figure A47. QQ plot for Sub CTW 1981.

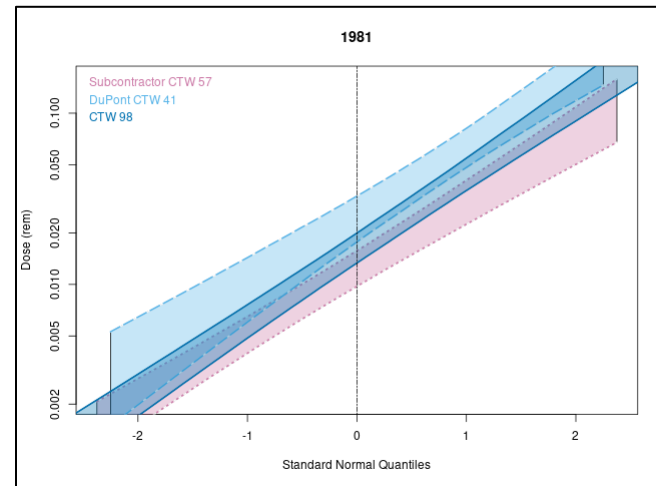


Figure A49. Band plot for 1981.



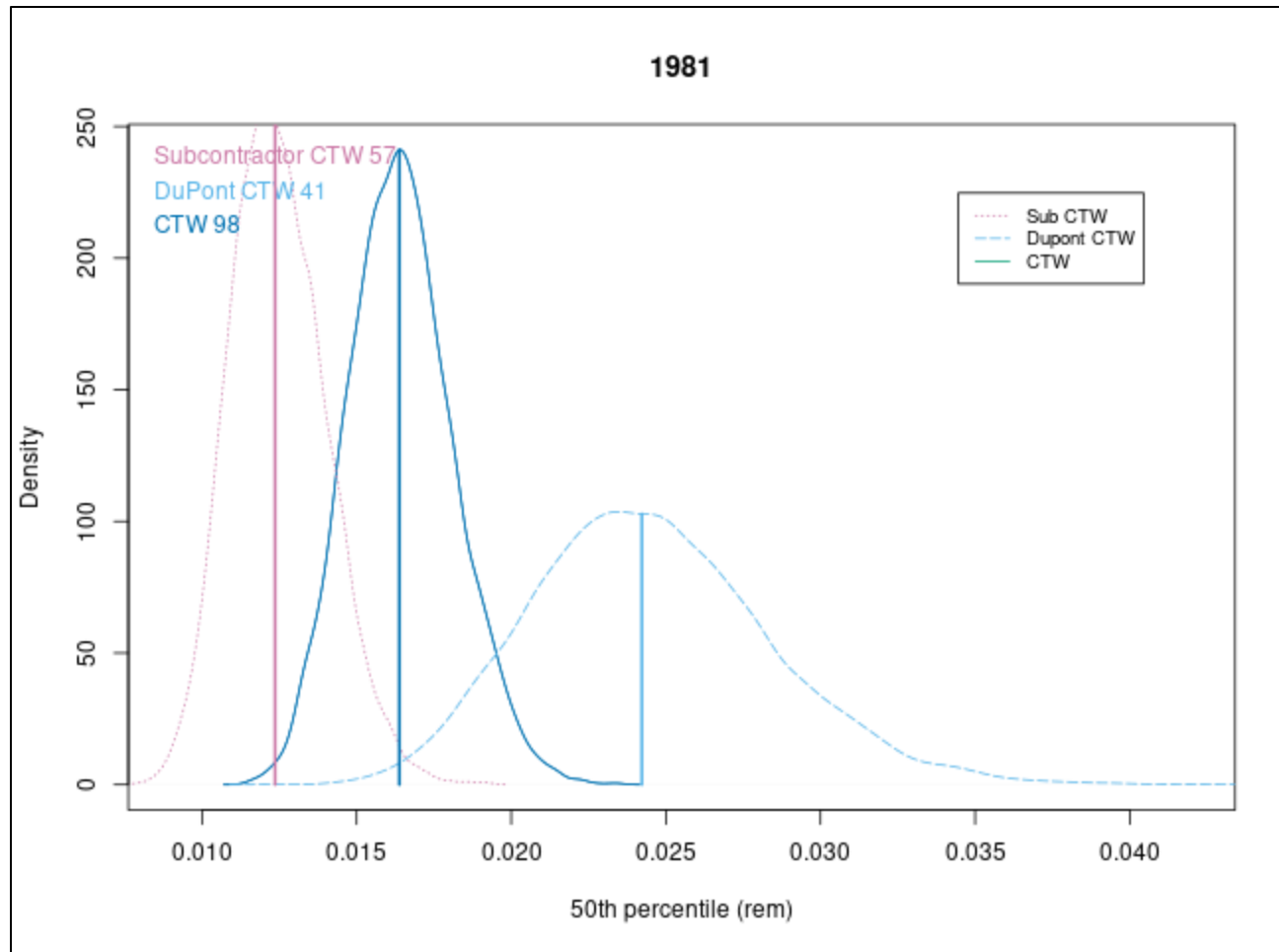


Figure A50. Density plot for 1981.

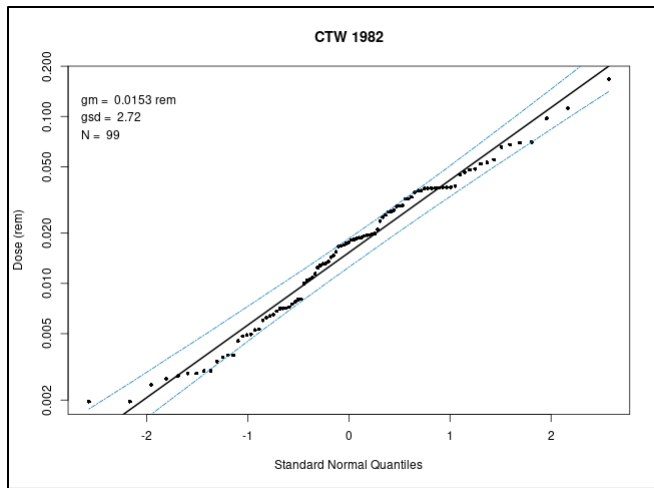


Figure A51. QQ plot for CTW 1982.

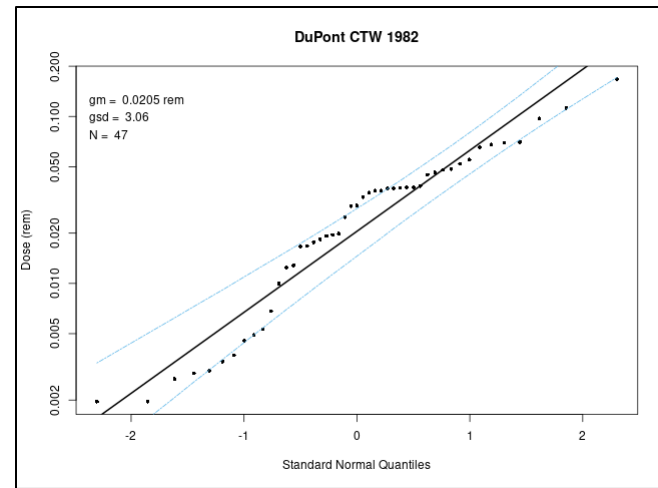


Figure A53. QQ plot for DuPont CTW 1982.

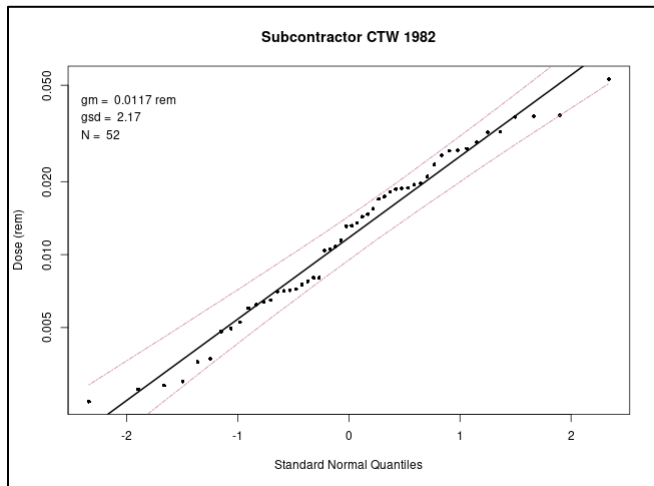


Figure A52. QQ plot for Sub CTW 1982.

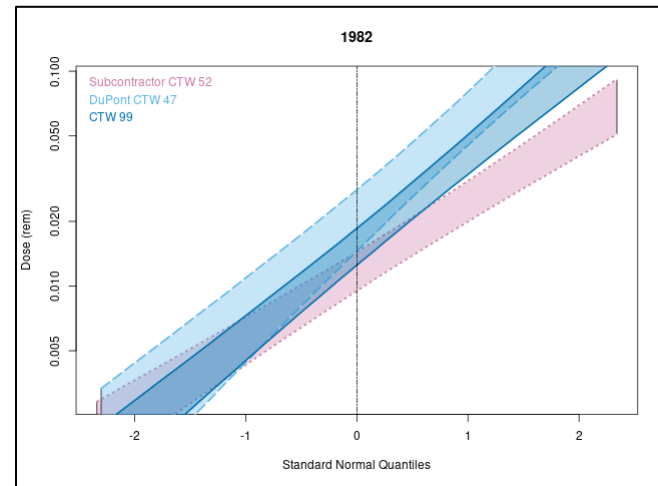


Figure A54. Band plot for 1982.

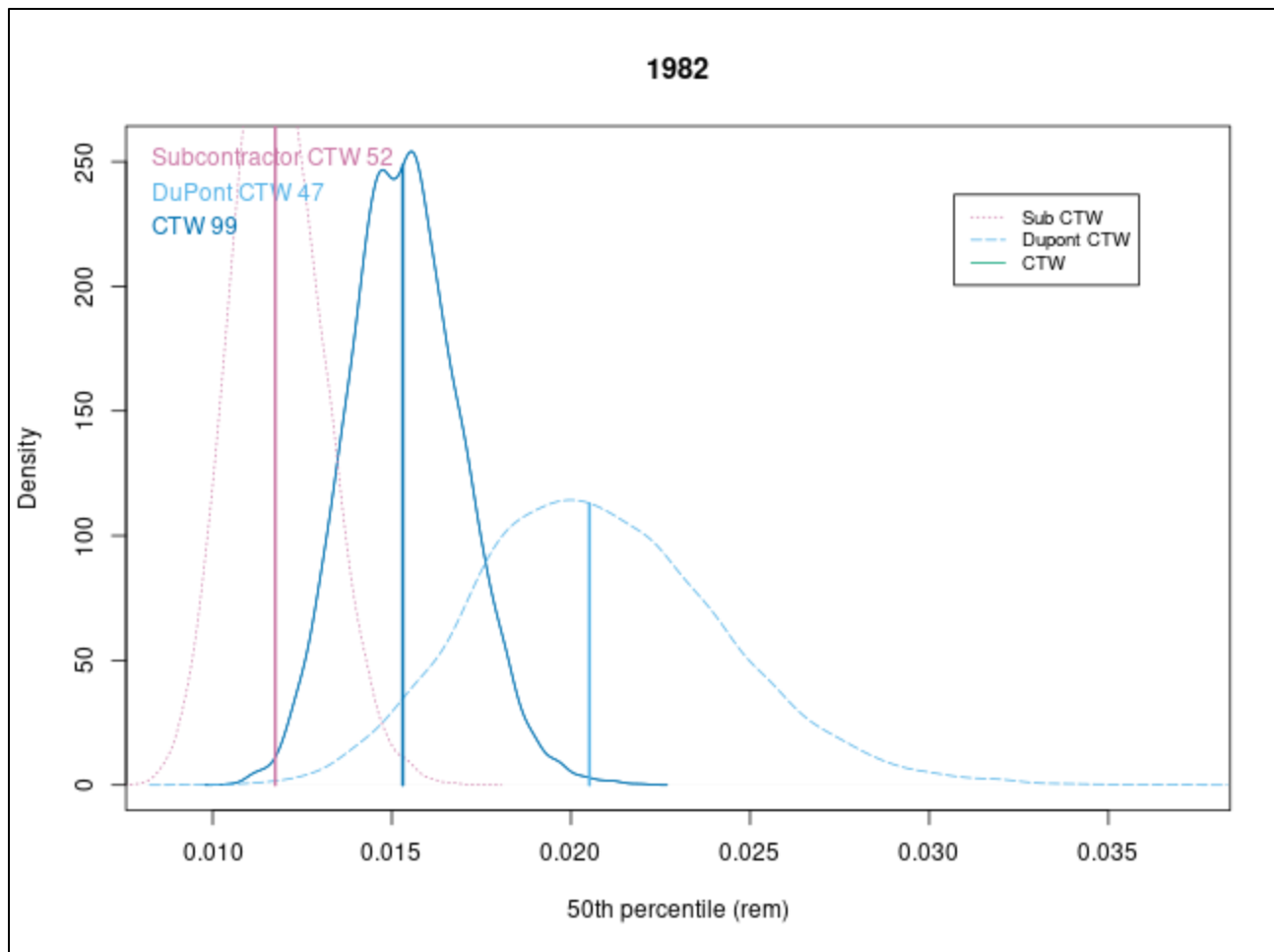


Figure A55. Density plot for 1982.

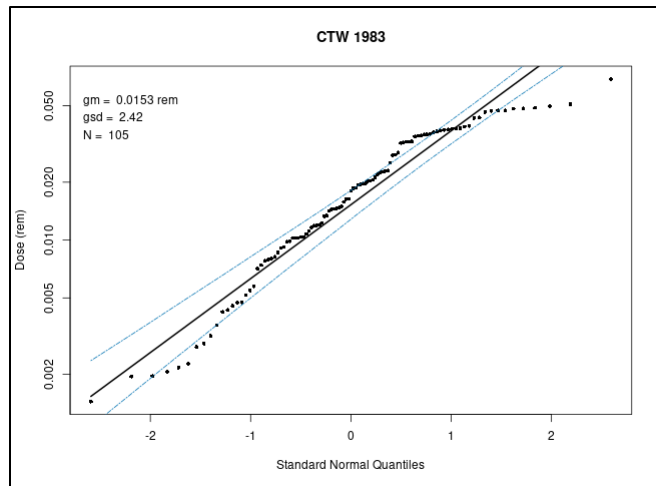


Figure A56. QQ plot for CTW 1983.

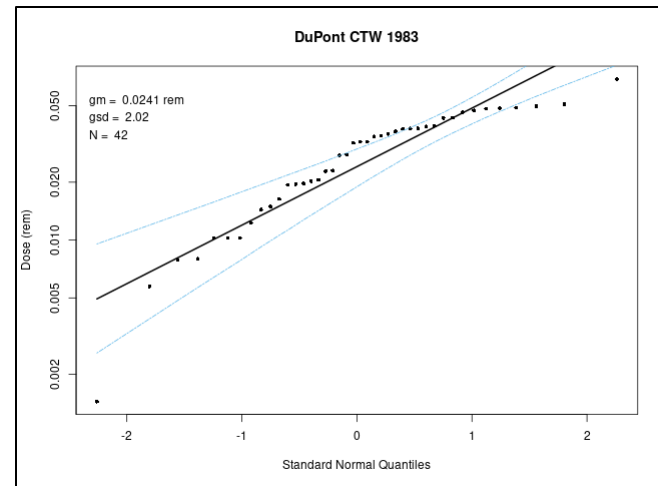


Figure A58. QQ plot for DuPont CTW 1983.

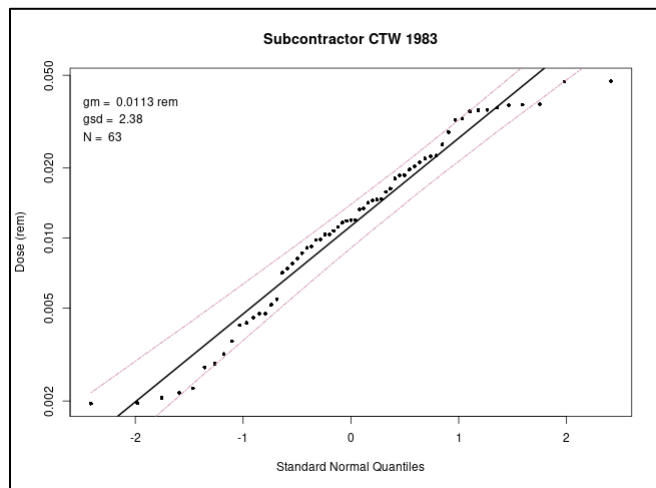


Figure A57. QQ plot for Sub CTW 1983.

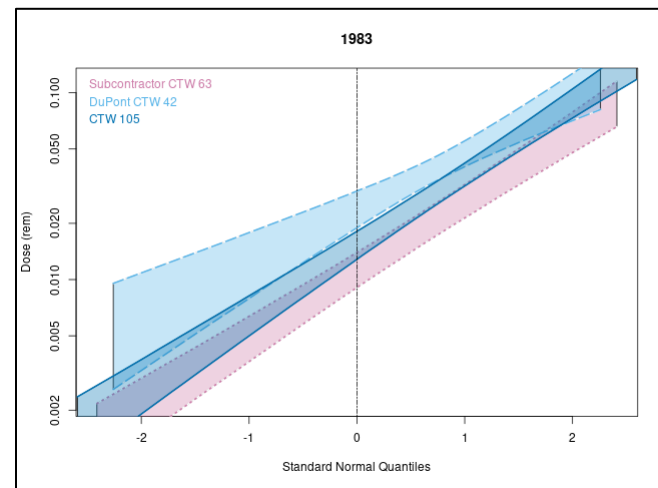


Figure A59. Band plot for 1983.

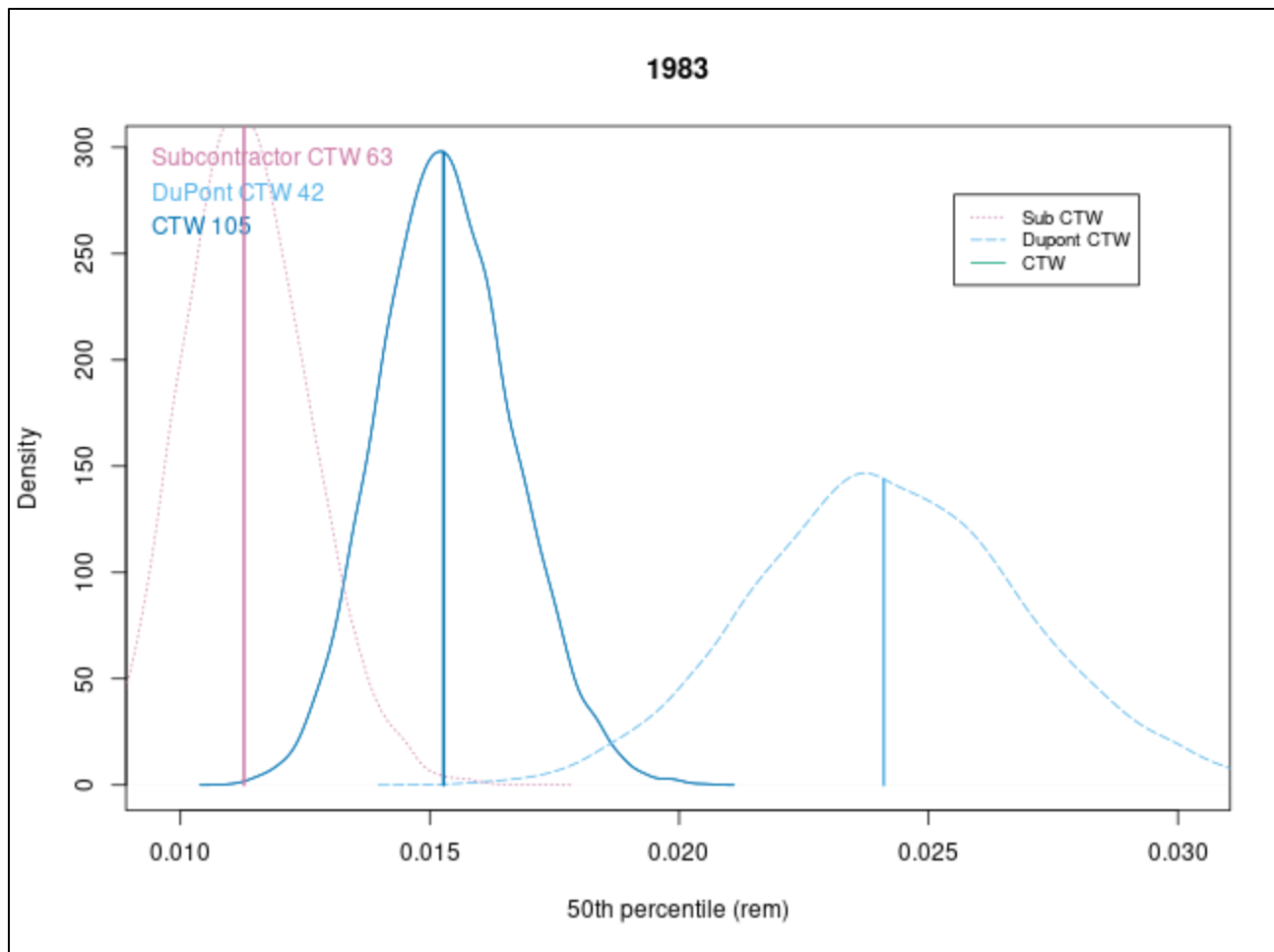


Figure A60. Density plot for 1983.

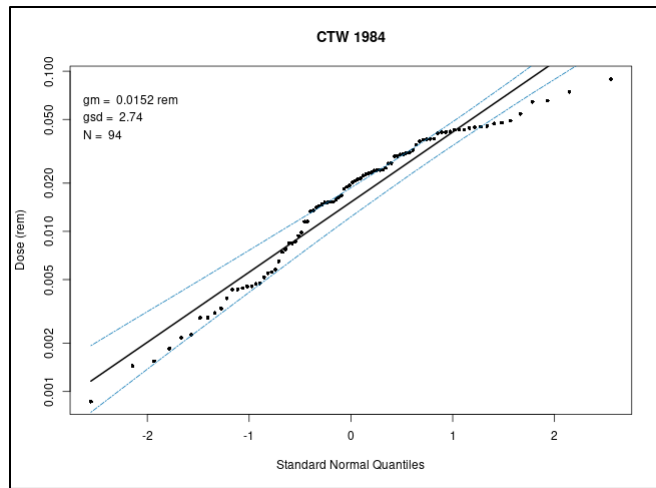


Figure A61. QQ plot for CTW 1984.

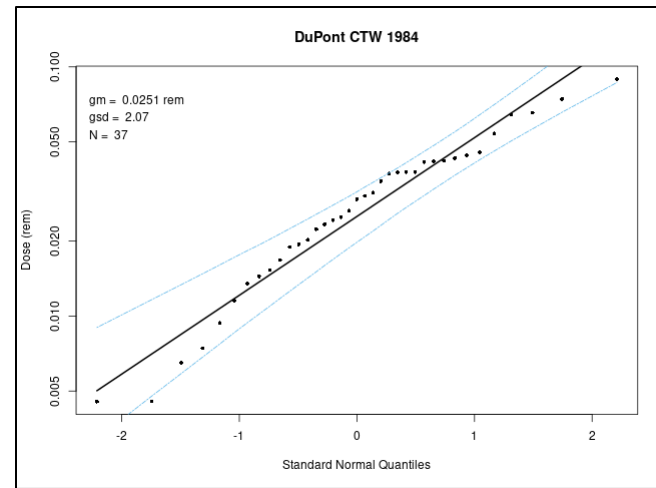


Figure A63. QQ plot for DuPont CTW 1984.

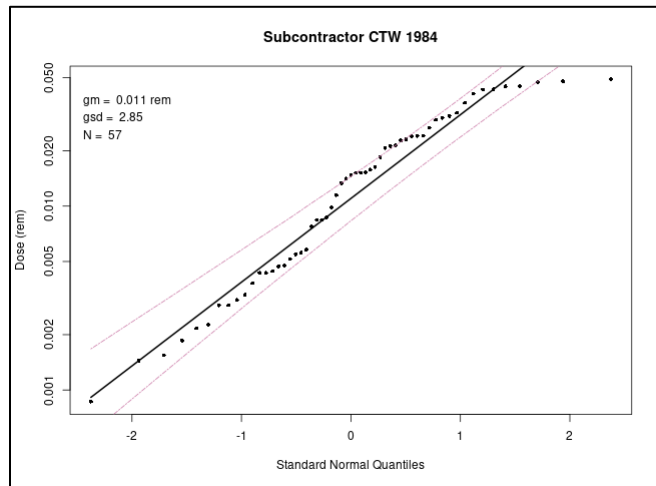


Figure A62. QQ plot for Sub CTW 1984.

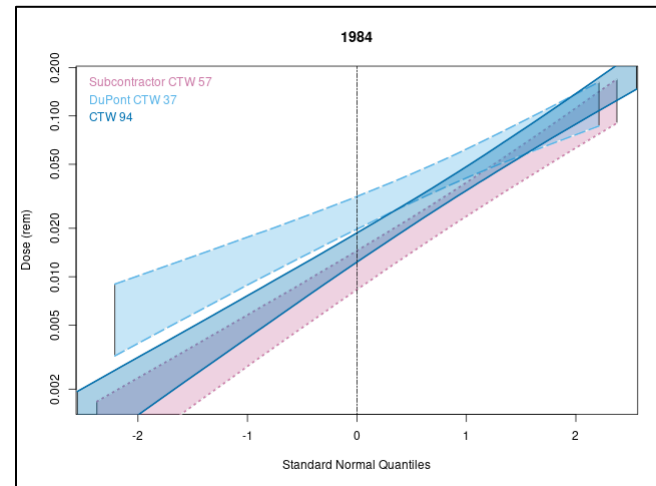


Figure A64. Band plot for 1984.

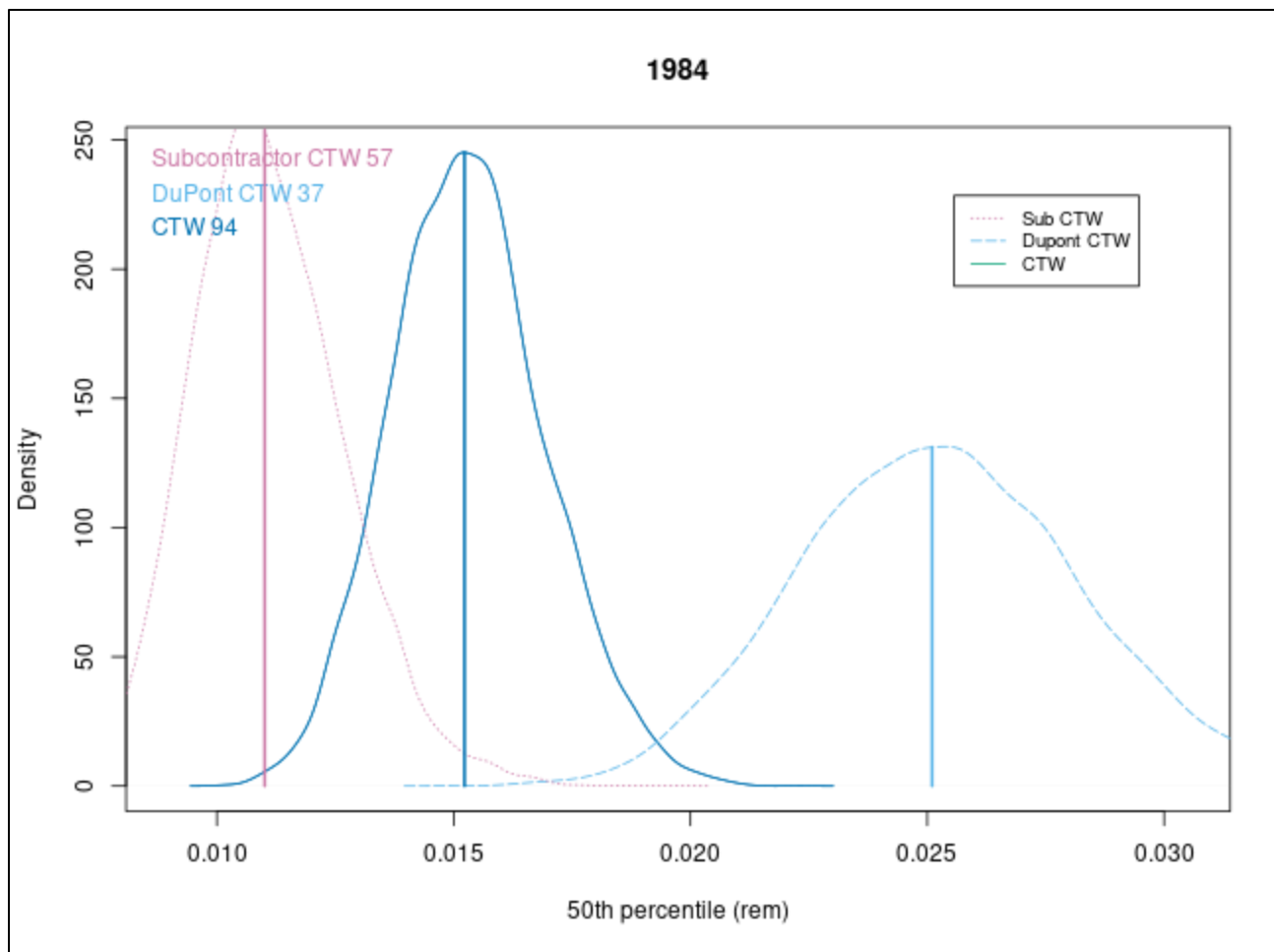


Figure A65. Density plot for 1984.

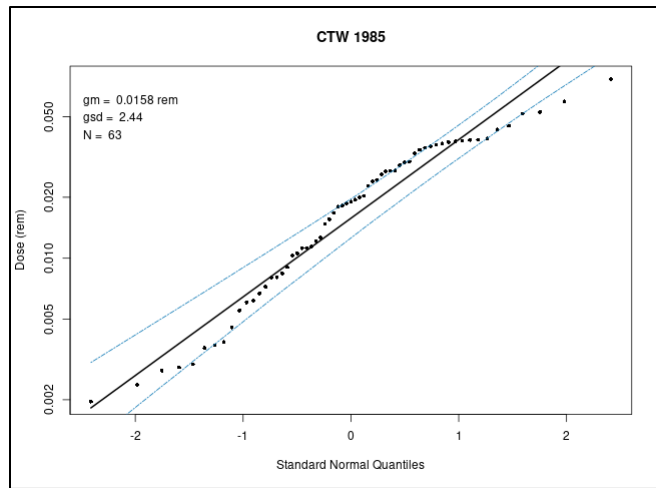


Figure A66. QQ plot for CTW 1985.

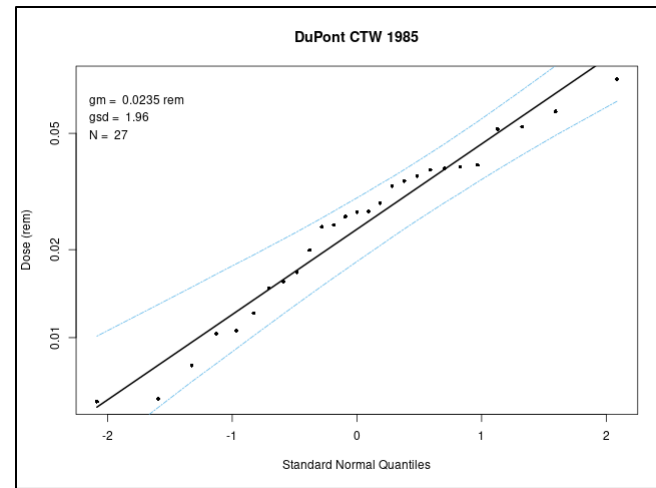


Figure A68. QQ plot for DuPont CTW 1985.

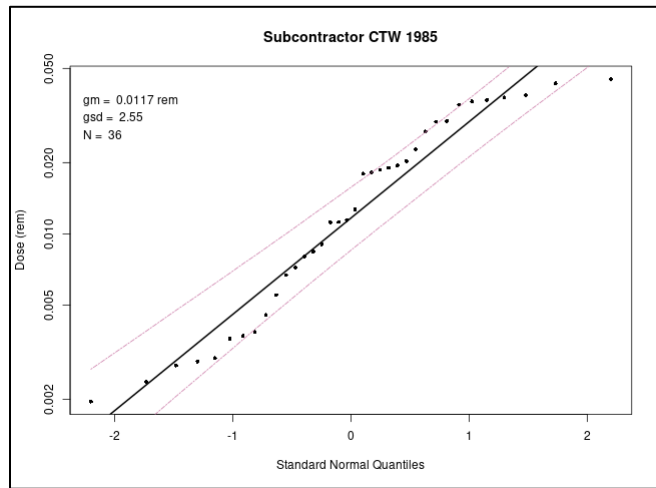


Figure A67. QQ plot for Sub CTW 1985.

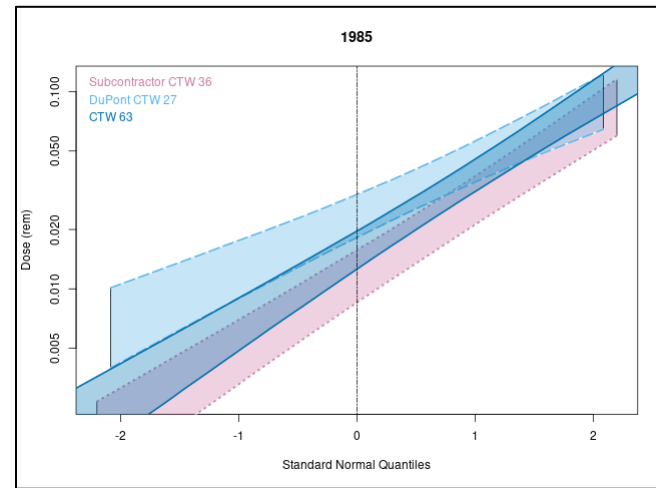


Figure A69. Band plot for 1985.



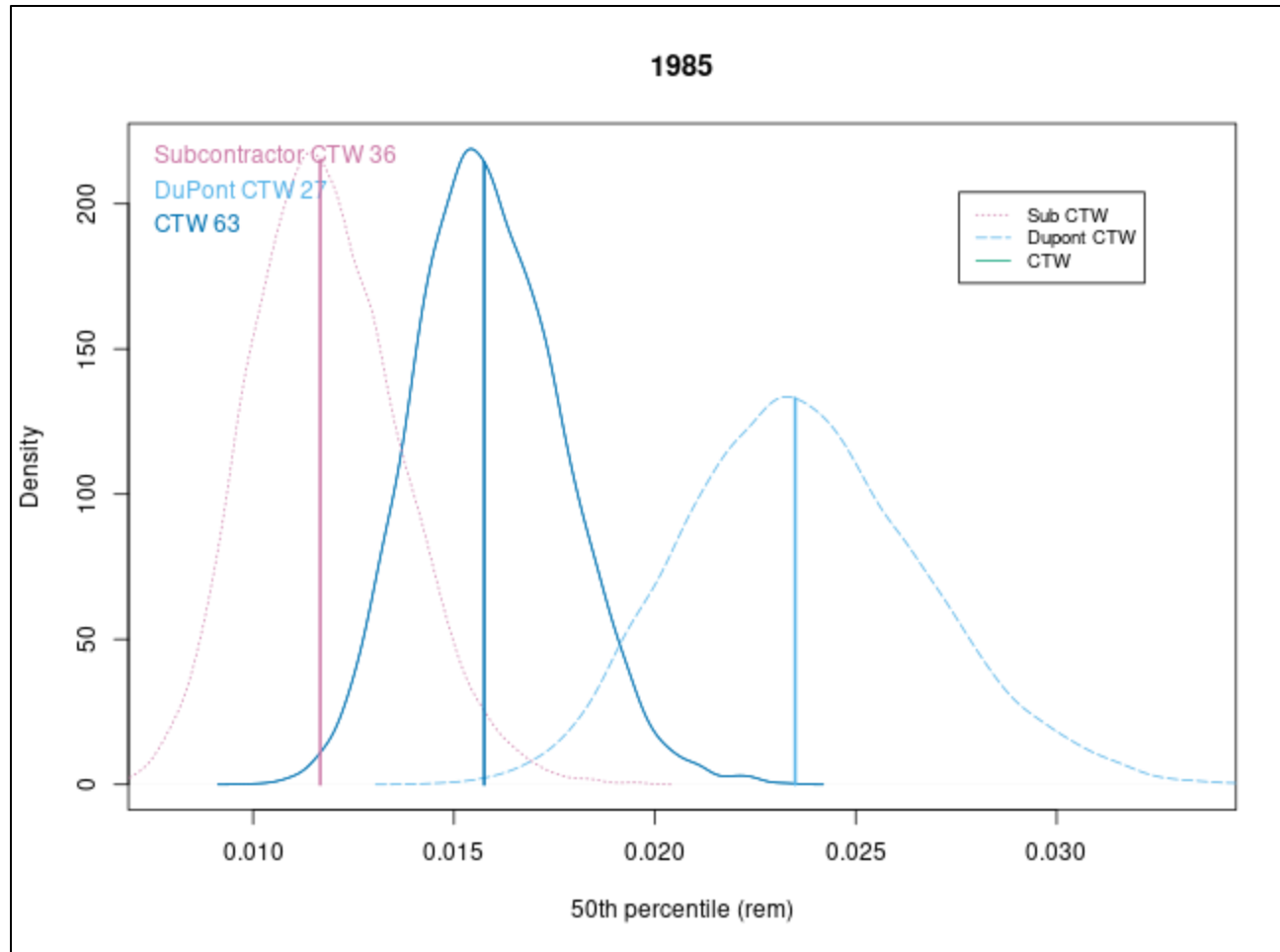


Figure A70. Density plot for 1985.

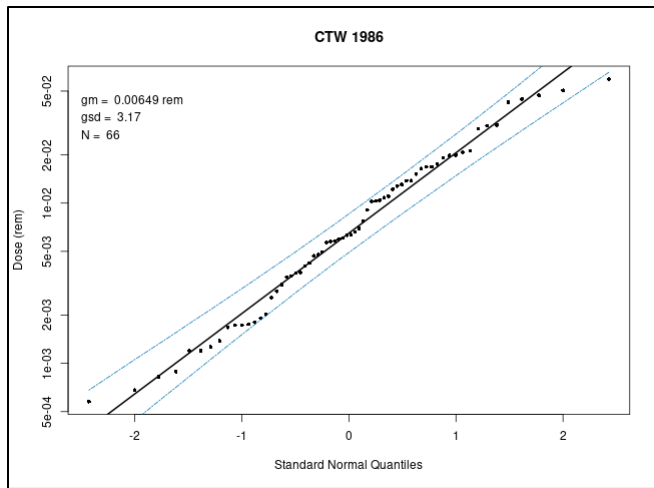


Figure A71. QQ plot for CTW 1986.

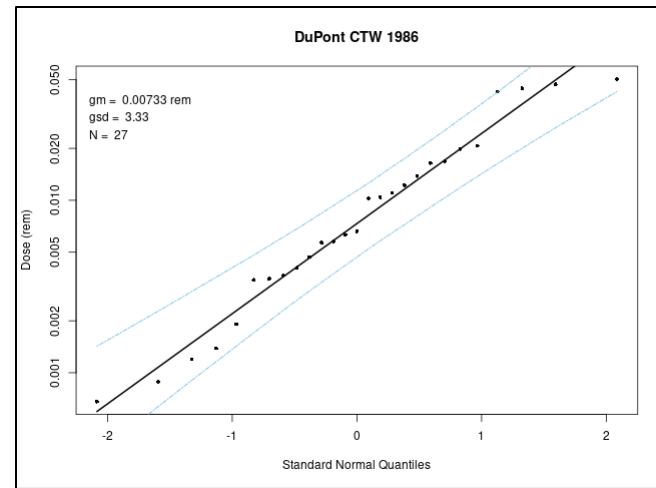


Figure A73. QQ plot for DuPont CTW 1986.

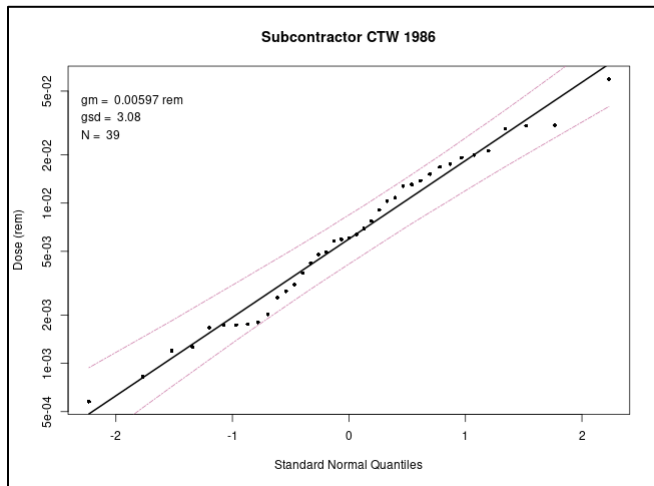


Figure A72. QQ plot for Sub CTW 1986.

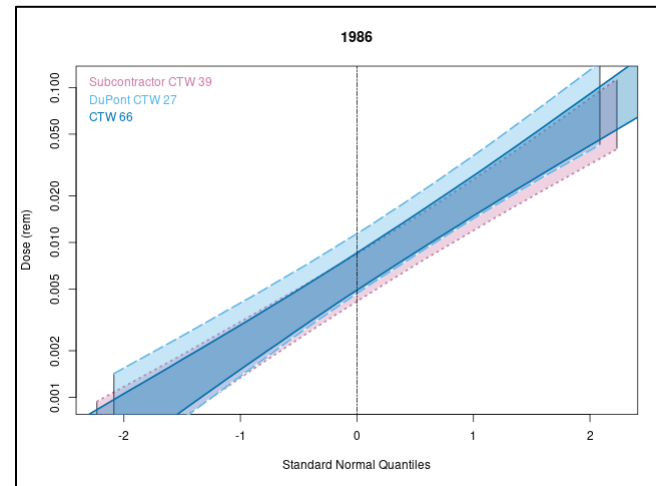


Figure A74. Band plot for 1986.

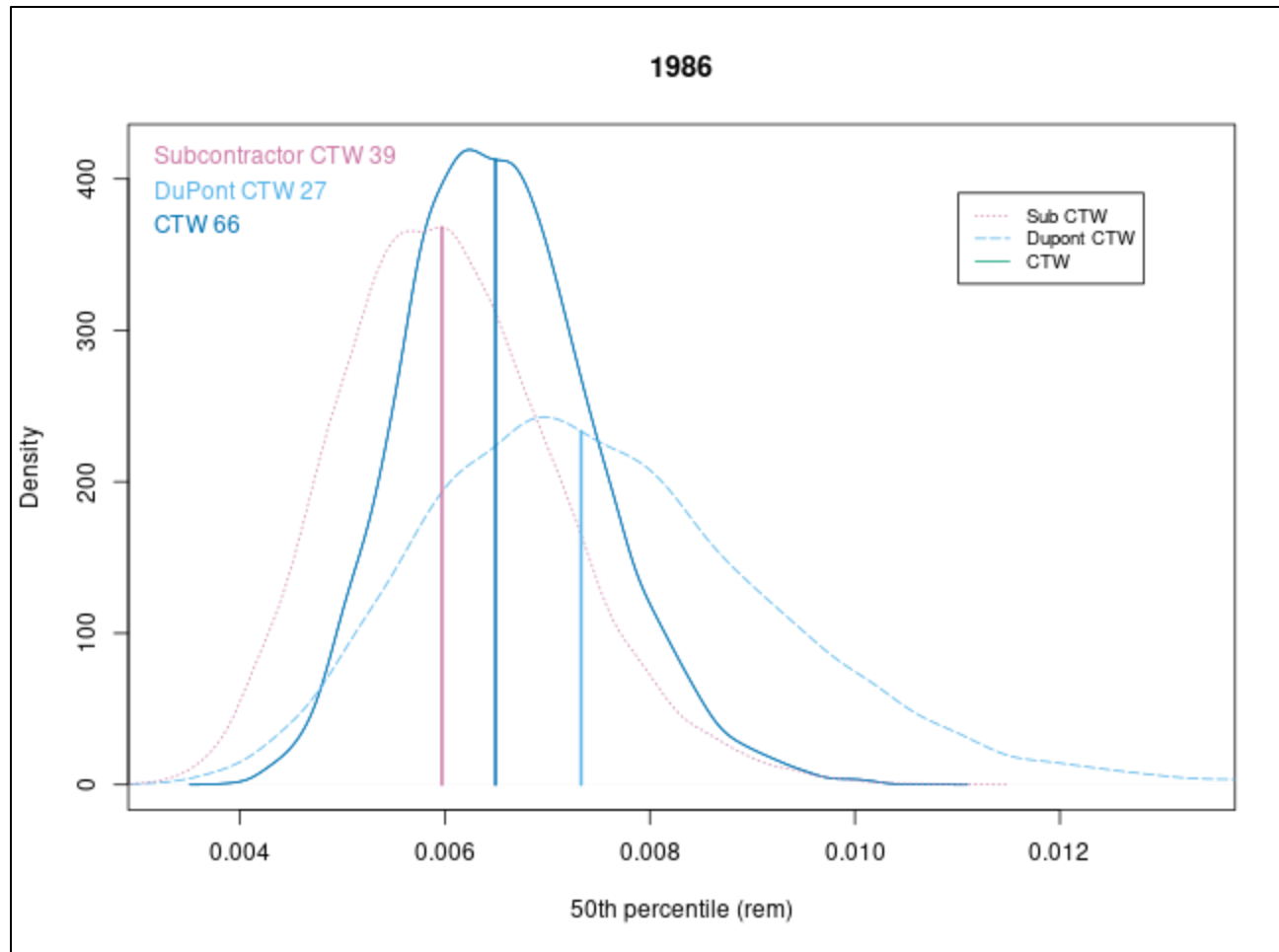


Figure A75. Density plot for 1986.

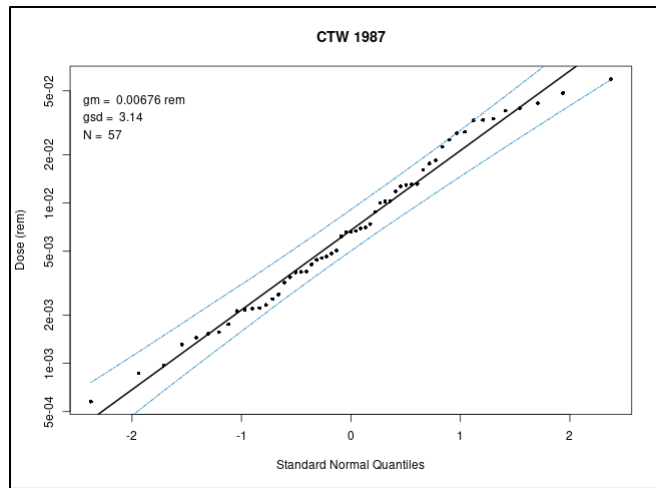


Figure A76. QQ plot for CTW 1987.

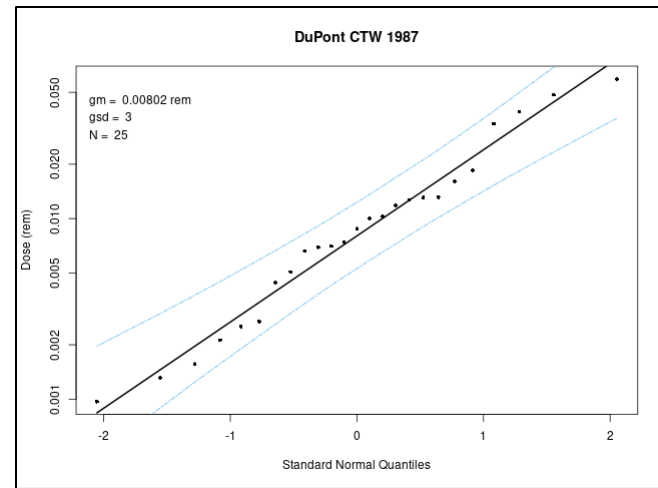


Figure A78. QQ plot for DuPont CTW 1987.

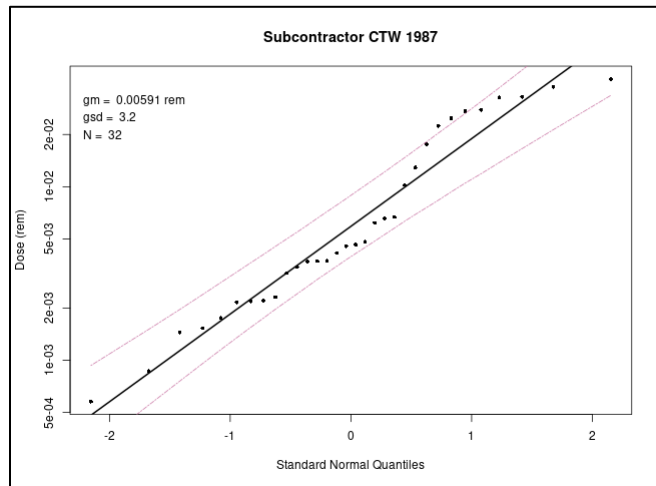


Figure A77. QQ plot for Sub CTW 1987.

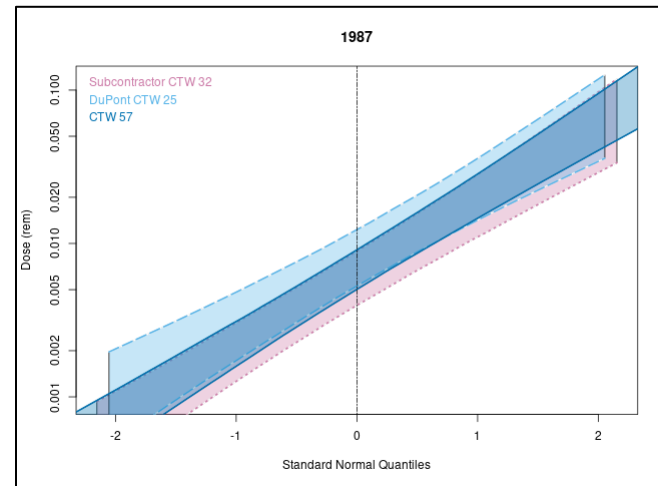


Figure A79. Band plot for 1987.

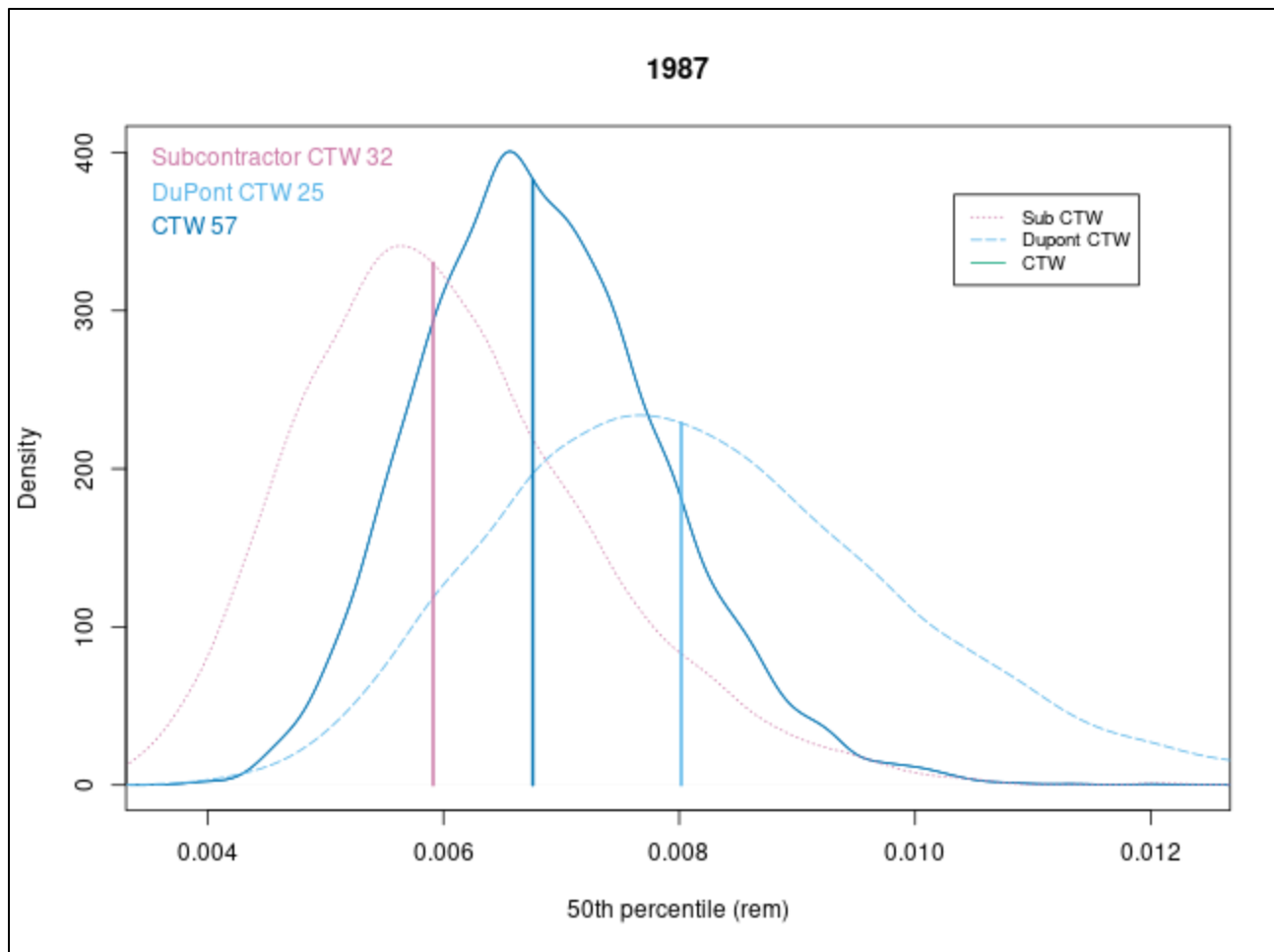


Figure A80. Density plot for 1987.

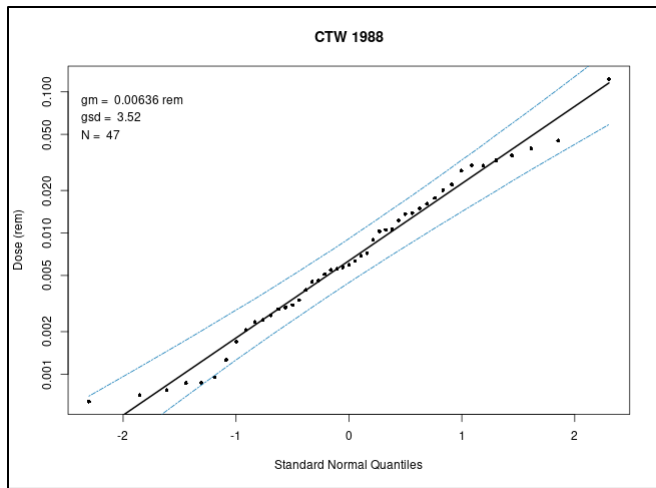


Figure A81. QQ plot for CTW 1988.

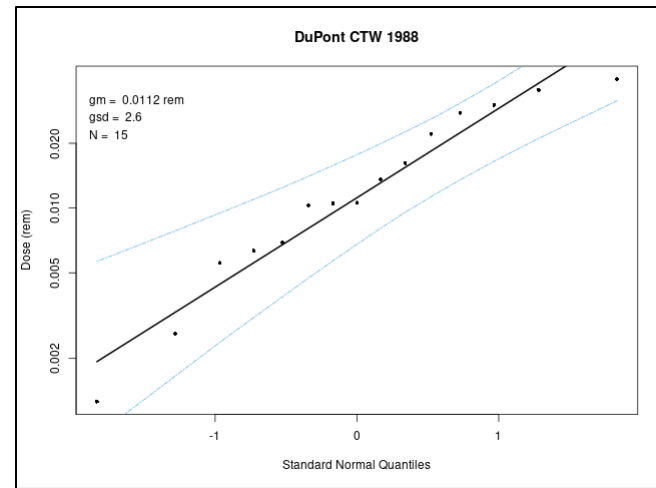


Figure A83. QQ plot for DuPont CTW 1988.

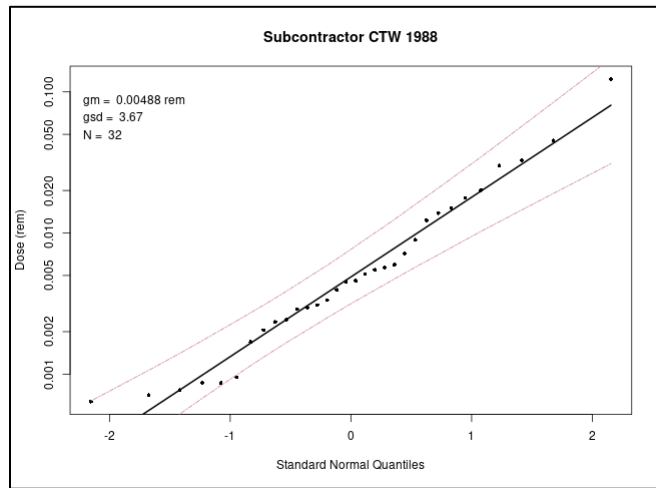


Figure A82. QQ plot for Sub CTW 1988.

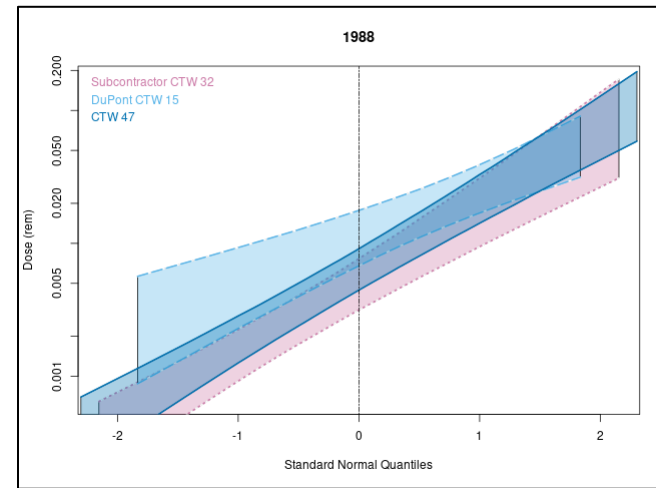


Figure A84. Band plot for 1988.

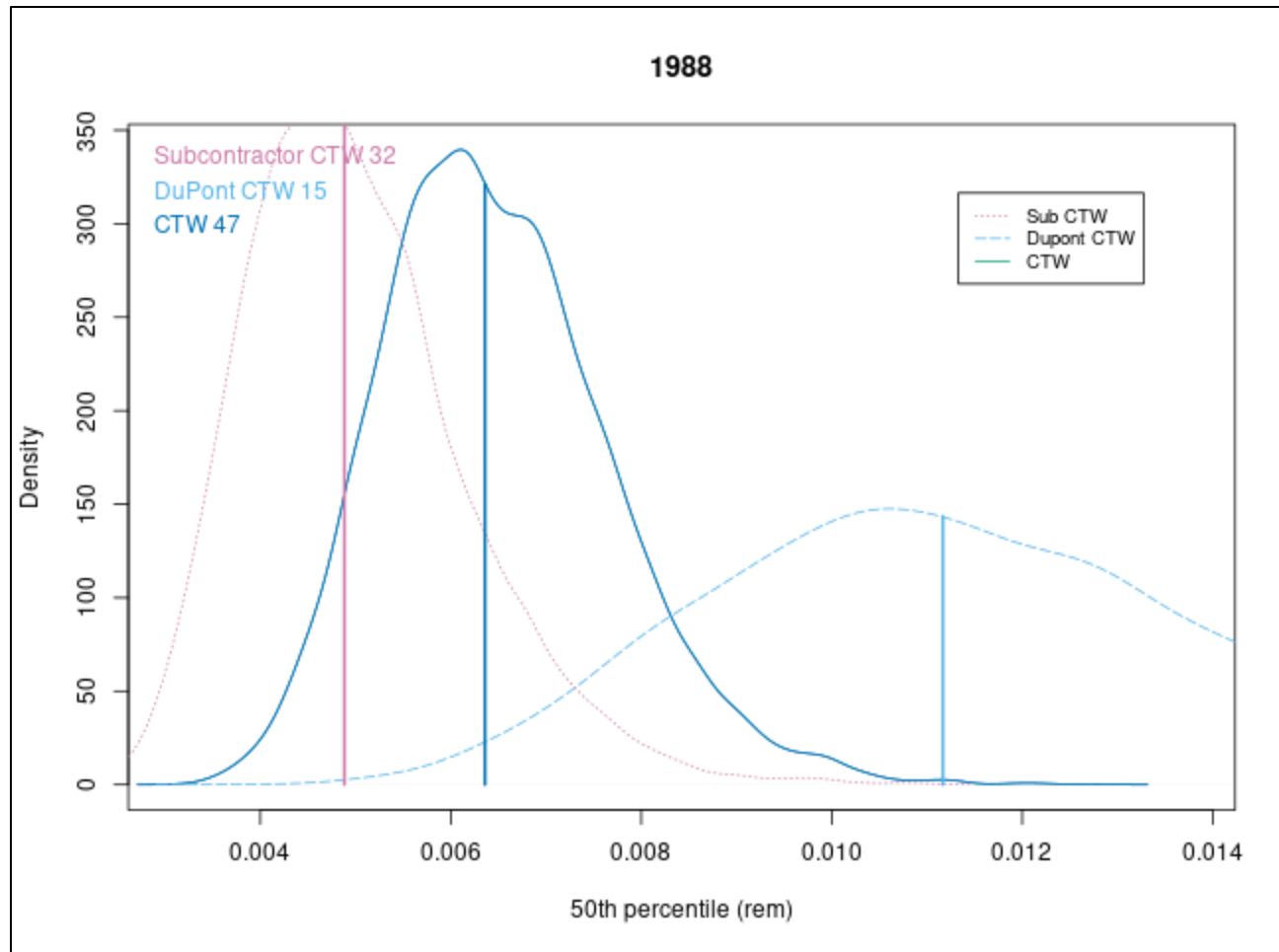


Figure A85. Density plot for 1988.

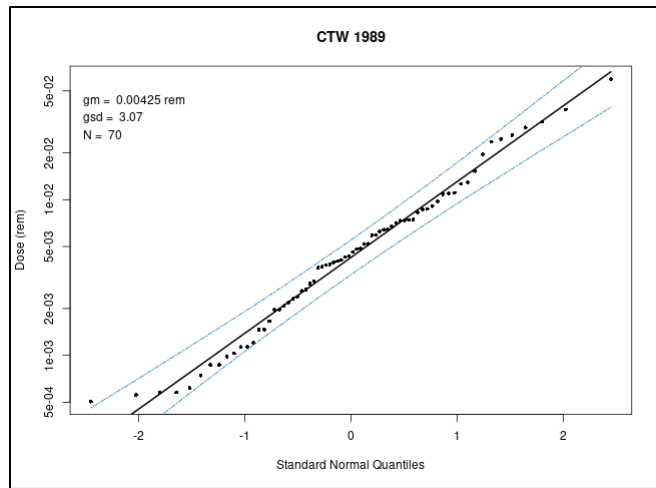


Figure A86. QQ plot for CTW 1989.

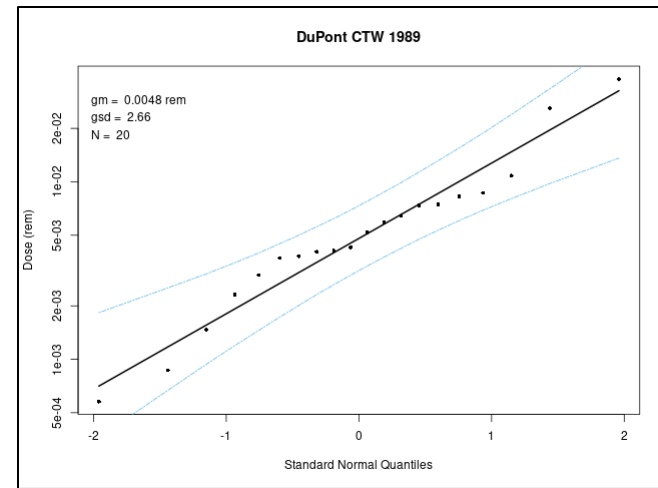


Figure A88. QQ plot for DuPont CTW 1989.

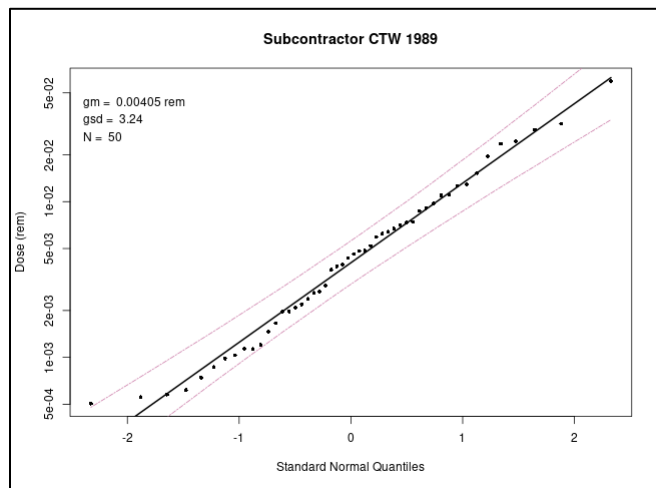


Figure A87. QQ plot for Sub CTW 1989.

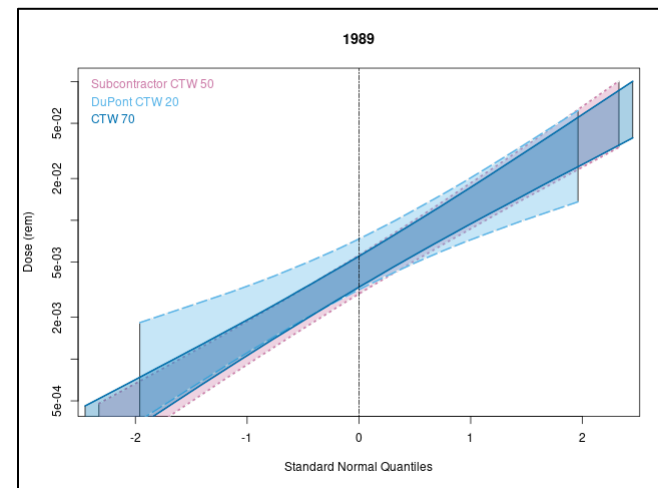


Figure A89. Band plot for 1989.



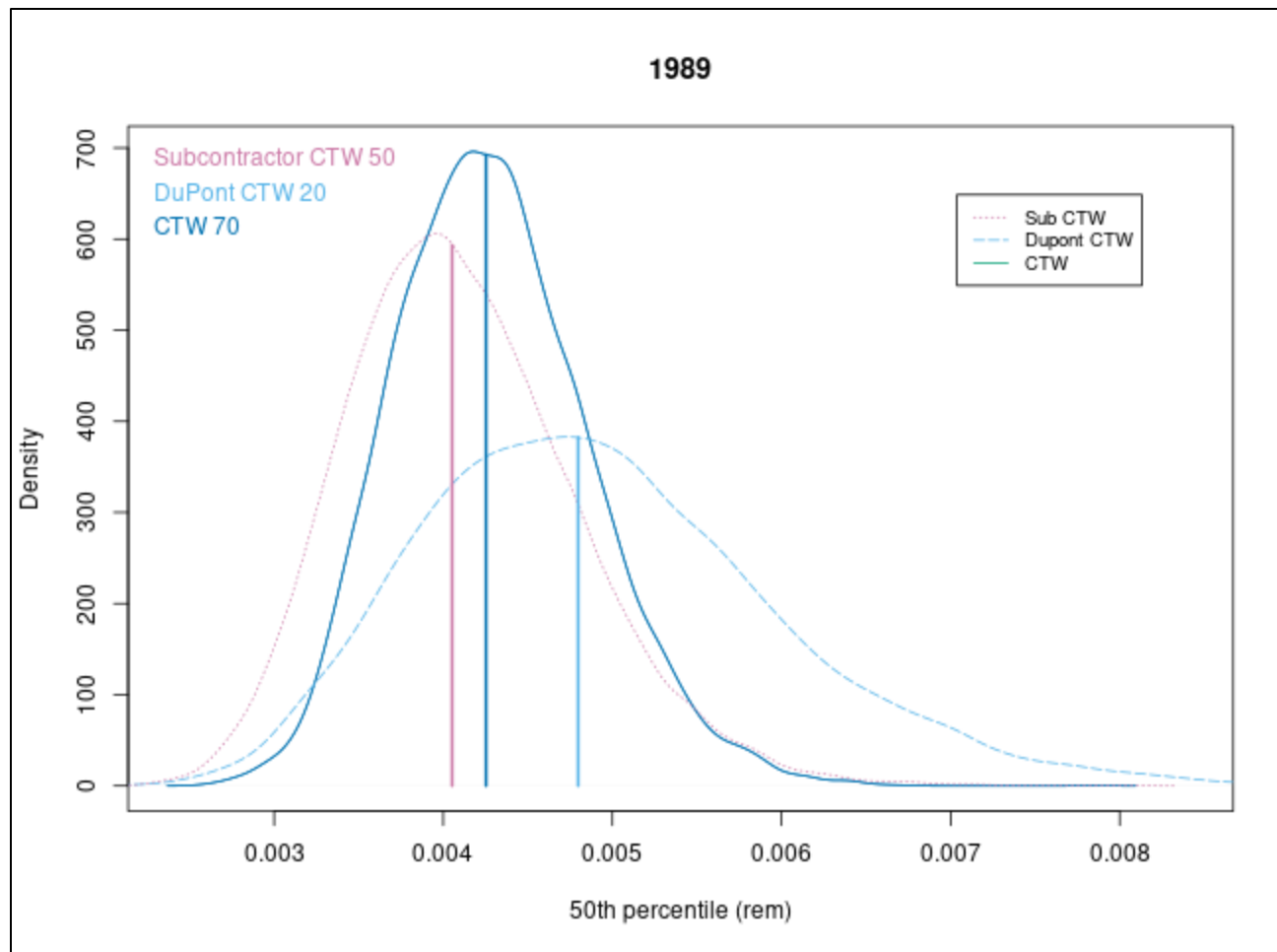


Figure A90. Density plot for 1989.

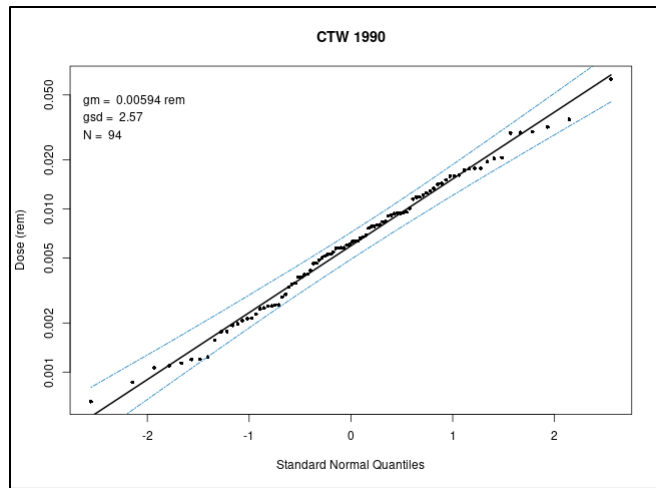


Figure A91. QQ plot for CTW 1990.

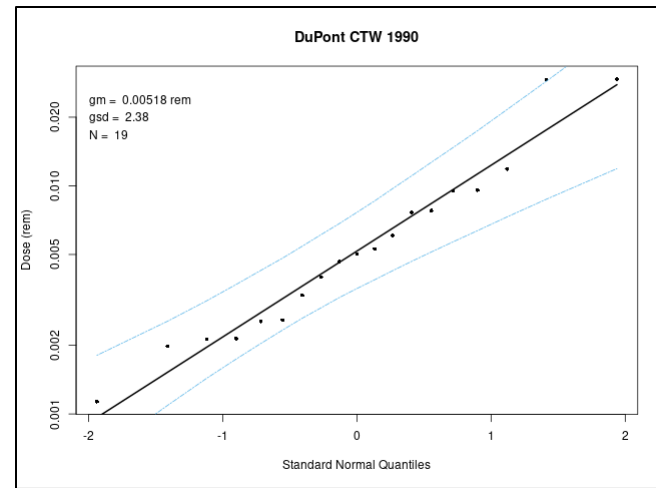


Figure A93. QQ plot for DuPont CTW 1990.

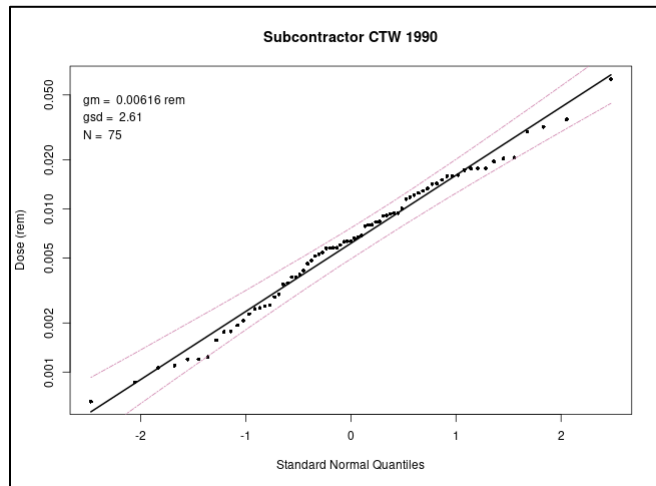


Figure A92. QQ plot for Sub CTW 1990.

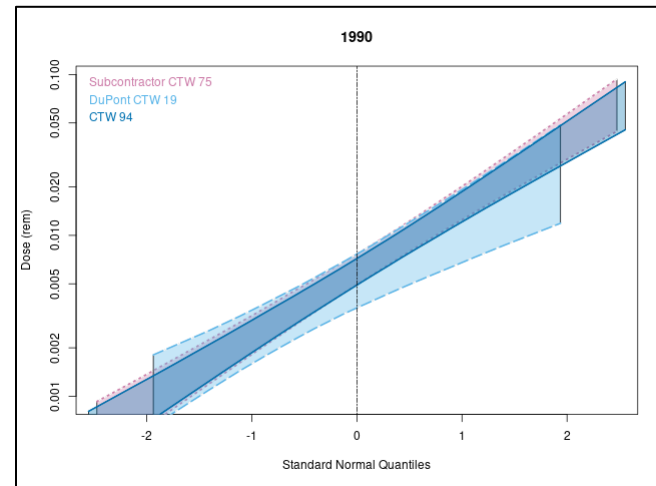


Figure A94. Band plot for 1990.

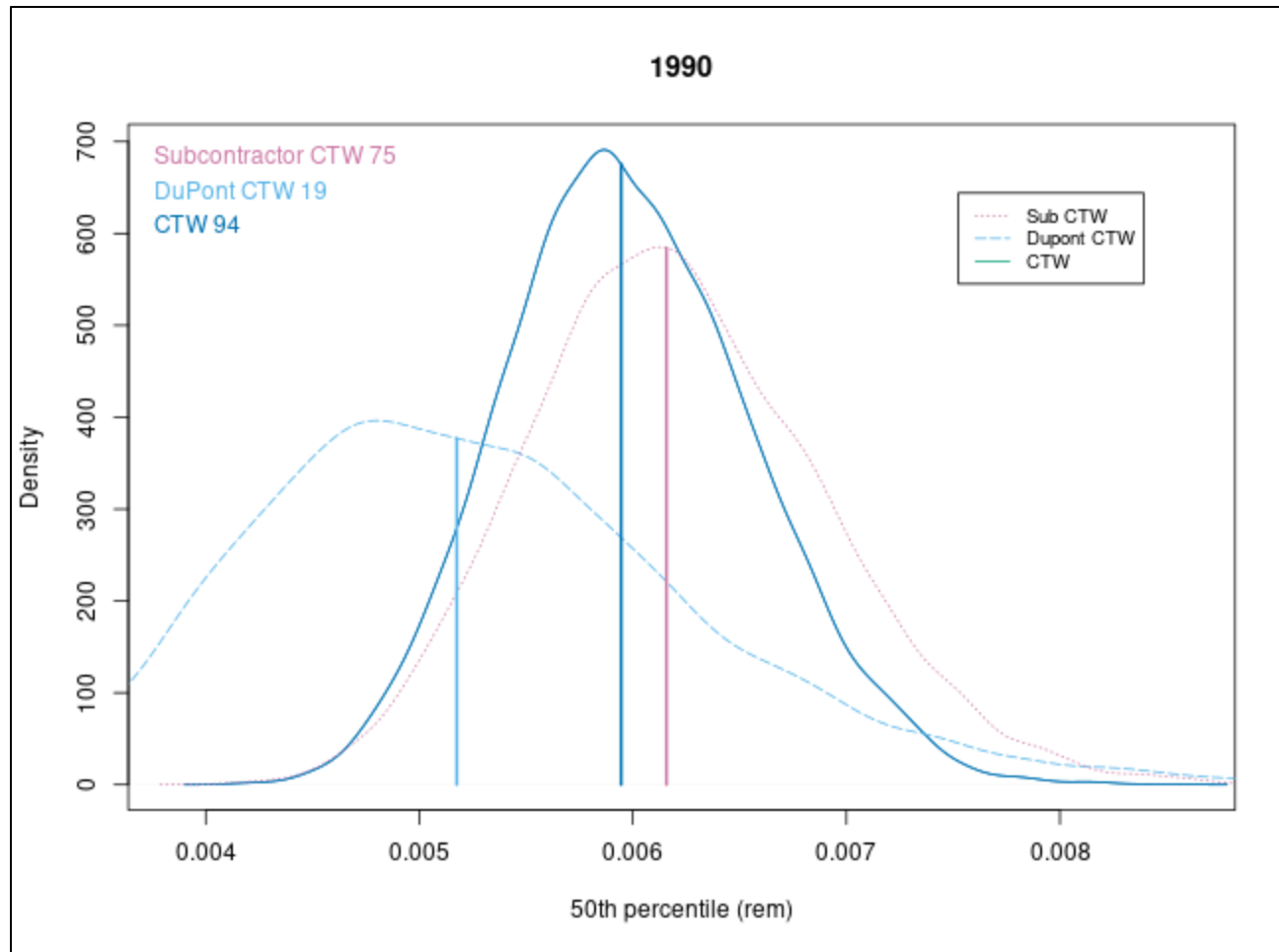


Figure A95. Density plot for 1990.

**APPENDIX B: Estimates and 95% confidence intervals for GM, 84th, and 95th for each group of workers in all years.****Table B1. Estimates and 95% confidence intervals for GM, 84th, and 95th for each group of workers in all years.**

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1954	CTW <sup>a</sup>	0.0093	0.0116	0.0145	0.0170	0.0221	0.0271	0.0245	0.0333	0.0421
1954	nonCTW	0.0105	0.0120	0.0136	0.0193	0.0222	0.0252	0.0281	0.0331	0.0383
1954	All Workers	0.0106	0.0118	0.0132	0.0196	0.0222	0.0248	0.0289	0.0333	0.0376
1955	Sub CTW	0.0081	0.0113	0.0149	0.0162	0.0200	0.0232	0.0223	0.0289	0.0350
1955	DuPont CTW	0.0136	0.0175	0.0224	0.0277	0.0381	0.0524	0.0424	0.0628	0.0932
1955	CTW	0.0125	0.0152	0.0186	0.0254	0.0326	0.0425	0.0388	0.0533	0.0747
1955	nonCTW	0.0112	0.0131	0.0151	0.0232	0.0272	0.0315	0.0357	0.0436	0.0528
1955	All Workers	0.0122	0.0138	0.0155	0.0256	0.0293	0.0336	0.0400	0.0477	0.0570
1956	Sub CTW	0.0115	0.0169	0.0235	0.0210	0.0305	0.0406	0.0277	0.0445	0.0649
1956	DuPont CTW	0.0121	0.0164	0.0222	0.0301	0.0432	0.0603	0.0528	0.0807	0.1193
1956	CTW	0.0127	0.0165	0.0211	0.0303	0.0407	0.0538	0.0515	0.0730	0.1016
1956	nonCTW	0.0154	0.0191	0.0237	0.0374	0.0502	0.0674	0.0653	0.0939	0.1346
1956	All Workers	0.0153	0.0180	0.0213	0.0377	0.0468	0.0576	0.0669	0.0864	0.1115
1957	Sub CTW	0.0180	0.0236	0.0311	0.0451	0.0616	0.0829	0.0795	0.1142	0.1621
1957	DuPont CTW	0.0214	0.0265	0.0332	0.0488	0.0651	0.0862	0.0817	0.1161	0.1632
1957	CTW	0.0212	0.0252	0.0299	0.0517	0.0641	0.0790	0.0905	0.1171	0.1507
1957	nonCTW	0.0213	0.0248	0.0288	0.0571	0.0677	0.0806	0.1048	0.1293	0.1610
1957	All Workers	0.0222	0.0249	0.0280	0.0580	0.0665	0.0761	0.1057	0.1252	0.1475
1958	Sub CTW	0.0186	0.0232	0.0292	0.0415	0.0553	0.0720	0.0689	0.0971	0.1315
1958	DuPont CTW	0.0320	0.0377	0.0440	0.0718	0.0815	0.0914	0.1159	0.1339	0.1540
1958	CTW	0.0273	0.0313	0.0358	0.0643	0.0733	0.0826	0.1100	0.1266	0.1444
1958	nonCTW	0.0313	0.0353	0.0395	0.0773	0.0862	0.0963	0.1351	0.1534	0.1752
1958	All Workers	0.0308	0.0337	0.0366	0.0746	0.0812	0.0883	0.1300	0.1432	0.1579
1959	Sub CTW	0.0049	0.0110	0.0247	0.0059	0.0303	0.0490	0.0067	0.0552	0.0931

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1959	DuPont CTW	0.0325	0.0397	0.0477	0.0901	0.1061	0.1227	0.1667	0.1998	0.2376
1959	CTW	0.0311	0.0379	0.0457	0.0877	0.1038	0.1205	0.1650	0.1986	0.2354
1959	nonCTW	0.0293	0.0340	0.0394	0.0894	0.1021	0.1160	0.1787	0.2073	0.2390
1959	All Workers	0.0313	0.0353	0.0396	0.0928	0.1030	0.1136	0.1833	0.2055	0.2295
1960	Sub CTW	0.0154	0.0220	0.0320	0.0371	0.0617	0.0997	0.0633	0.1199	0.2131
1960	DuPont CTW	0.0409	0.0495	0.0601	0.1172	0.1434	0.1761	0.2225	0.2846	0.3663
1960	CTW	0.0346	0.0415	0.0498	0.1040	0.1264	0.1535	0.2057	0.2590	0.3269
1960	nonCTW	0.0392	0.0459	0.0533	0.1258	0.1444	0.1644	0.2553	0.3025	0.3574
1960	All Workers	0.0393	0.0441	0.0496	0.1230	0.1381	0.1542	0.2500	0.2882	0.3298
1961	Sub CTW	0.0139	0.0199	0.0288	0.0401	0.0639	0.0984	0.0760	0.1360	0.2275
1961	DuPont CTW	0.0379	0.0480	0.0601	0.1233	0.1502	0.1800	0.2517	0.3128	0.3841
1961	CTW	0.0303	0.0374	0.0456	0.1043	0.1273	0.1523	0.2247	0.2802	0.3426
1961	nonCTW	0.0437	0.0504	0.0580	0.1290	0.1460	0.1647	0.2500	0.2893	0.3358
1961	All Workers	0.0399	0.0449	0.0504	0.1263	0.1400	0.1549	0.2590	0.2918	0.3281
1962	Sub CTW	0.0295	0.0374	0.0472	0.0823	0.1069	0.1360	0.1559	0.2104	0.2774
1962	DuPont CTW	0.0363	0.0442	0.0532	0.0996	0.1174	0.1374	0.1807	0.2203	0.2675
1962	CTW	0.0354	0.0411	0.0478	0.0989	0.1145	0.1315	0.1869	0.2214	0.2610
1962	nonCTW	0.0452	0.0515	0.0586	0.1274	0.1440	0.1614	0.2416	0.2795	0.3210
1962	All Workers	0.0423	0.0468	0.0516	0.1197	0.1314	0.1442	0.2294	0.2560	0.2850
1963	Sub CTW	0.0329	0.0415	0.0515	0.0887	0.1063	0.1258	0.1574	0.1951	0.2397
1963	DuPont CTW	0.0320	0.0386	0.0466	0.0868	0.1067	0.1326	0.1610	0.2053	0.2686
1963	CTW	0.0343	0.0397	0.0458	0.0929	0.1075	0.1250	0.1722	0.2043	0.2464
1963	nonCTW	0.0425	0.0484	0.0546	0.1114	0.1232	0.1360	0.1970	0.2250	0.2592
1963	All Workers	0.0403	0.0444	0.0487	0.1080	0.1173	0.1277	0.1981	0.2194	0.2457
1964	Sub CTW	0.0517	0.0657	0.0822	0.1267	0.1590	0.1949	0.2121	0.2810	0.3619
1964	DuPont CTW	0.0380	0.0477	0.0594	0.1152	0.1417	0.1704	0.2265	0.2856	0.3553

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1964	CTW	0.0454	0.0537	0.0628	0.1295	0.1507	0.1729	0.2464	0.2926	0.3449
1964	nonCTW	0.0518	0.0606	0.0705	0.1598	0.1810	0.2025	0.3184	0.3661	0.4189
1964	All Workers	0.0513	0.0575	0.0641	0.1531	0.1683	0.1839	0.3008	0.3363	0.3735
1965	Sub CTW	0.0212	0.0281	0.0362	0.0480	0.0609	0.0772	0.0748	0.1001	0.1364
1965	DuPont CTW	0.0410	0.0522	0.0665	0.1181	0.1529	0.1949	0.2257	0.3046	0.4077
1965	CTW	0.0352	0.0429	0.0520	0.0977	0.1216	0.1507	0.1822	0.2382	0.3089
1965	nonCTW	0.0454	0.0546	0.0653	0.1563	0.1832	0.2108	0.3347	0.3993	0.4675
1965	All Workers	0.0436	0.0498	0.0570	0.1403	0.1597	0.1801	0.2912	0.3379	0.3888
1966	Sub CTW	0.0109	0.0163	0.0242	0.0269	0.0420	0.0609	0.0464	0.0770	0.1177
1966	DuPont CTW	0.0288	0.0375	0.0482	0.0885	0.1126	0.1380	0.1759	0.2284	0.2879
1966	CTW	0.0244	0.0308	0.0387	0.0756	0.0949	0.1165	0.1522	0.1964	0.2456
1966	nonCTW	0.0394	0.0463	0.0538	0.1160	0.1316	0.1478	0.2249	0.2581	0.2938
1966	All Workers	0.0352	0.0400	0.0458	0.1068	0.1196	0.1332	0.2142	0.2419	0.2720
1967	Sub CTW	0.0096	0.0149	0.0240	0.0183	0.0363	0.0612	0.0275	0.0642	0.1143
1967	DuPont CTW	0.0317	0.0420	0.0543	0.0967	0.1167	0.1340	0.1878	0.2240	0.2614
1967	CTW	0.0266	0.0342	0.0437	0.0818	0.1010	0.1196	0.1661	0.2028	0.2385
1967	nonCTW	0.0428	0.0494	0.0567	0.1080	0.1202	0.1334	0.1871	0.2132	0.2432
1967	All Workers	0.0388	0.0440	0.0498	0.1059	0.1160	0.1268	0.1951	0.2165	0.2401
1968	Sub CTW	0.0133	0.0185	0.0249	0.0318	0.0425	0.0545	0.0518	0.0723	0.0978
1968	DuPont CTW	0.0280	0.0372	0.0488	0.0840	0.1096	0.1363	0.1653	0.2202	0.2782
1968	CTW	0.0236	0.0295	0.0368	0.0684	0.0863	0.1067	0.1323	0.1726	0.2188
1968	nonCTW	0.0433	0.0509	0.0594	0.1214	0.1389	0.1599	0.2250	0.2653	0.3167
1968	All Workers	0.0366	0.0418	0.0478	0.1077	0.1215	0.1368	0.2106	0.2417	0.2778
1969	Sub CTW	0.0137	0.0211	0.0318	0.0346	0.0557	0.0786	0.0604	0.1039	0.1479
1969	DuPont CTW	0.0262	0.0367	0.0510	0.0867	0.1204	0.1569	0.1819	0.2584	0.3435
1969	CTW	0.0239	0.0312	0.0406	0.0751	0.0999	0.1270	0.1532	0.2111	0.2756

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1969	nonCTW	0.0444	0.0517	0.0594	0.1121	0.1239	0.1356	0.1915	0.2178	0.2455
1969	All Workers	0.0384	0.0440	0.0501	0.1084	0.1200	0.1319	0.2048	0.2291	0.2555
1970	Sub CTW	0.0082	0.0133	0.0220	0.0145	0.0289	0.0464	0.0194	0.0478	0.0838
1970	DuPont CTW	0.0179	0.0250	0.0351	0.0617	0.0896	0.1227	0.1341	0.2030	0.2818
1970	CTW	0.0170	0.0230	0.0312	0.0552	0.0792	0.1088	0.1167	0.1766	0.2477
1970	nonCTW	0.0359	0.0423	0.0495	0.0977	0.1103	0.1224	0.1798	0.2041	0.2299
1970	All Workers	0.0303	0.0352	0.0407	0.0921	0.1045	0.1168	0.1848	0.2106	0.2366
1971	Sub CTW	0.0044	0.0079	0.0157	0.0069	0.0192	0.0393	0.0092	0.0335	0.0768
1971	DuPont CTW	0.0245	0.0332	0.0447	0.0728	0.1022	0.1389	0.1418	0.2110	0.2986
1971	CTW	0.0208	0.0282	0.0379	0.0653	0.0921	0.1259	0.1323	0.1970	0.2825
1971	nonCTW	0.0443	0.0505	0.0574	0.1025	0.1149	0.1286	0.1694	0.1953	0.2251
1971	All Workers	0.0376	0.0430	0.0489	0.1010	0.1134	0.1266	0.1856	0.2119	0.2423
1972	Sub CTW	0.0136	0.0257	0.0455	0.0392	0.0751	0.1364	0.0670	0.1506	0.3162
1972	DuPont CTW	0.0257	0.0347	0.0466	0.0866	0.1141	0.1438	0.1832	0.2447	0.3133
1972	CTW	0.0251	0.0329	0.0427	0.0836	0.1080	0.1352	0.1766	0.2321	0.2965
1972	nonCTW	0.0404	0.0469	0.0541	0.1187	0.1318	0.1449	0.2290	0.2562	0.2863
1972	All Workers	0.0373	0.0426	0.0484	0.1149	0.1266	0.1388	0.2305	0.2557	0.2831
1973	Sub CTW	0.0064	0.0114	0.0208	0.0138	0.0328	0.0640	0.0227	0.0643	0.1366
1973	DuPont CTW	0.0229	0.0315	0.0427	0.0813	0.1075	0.1338	0.1799	0.2355	0.2932
1973	CTW	0.0201	0.0268	0.0355	0.0717	0.0944	0.1188	0.1604	0.2126	0.2670
1973	nonCTW	0.0387	0.0448	0.0515	0.1130	0.1243	0.1360	0.2154	0.2401	0.2674
1973	All Workers	0.0342	0.0390	0.0445	0.1080	0.1186	0.1294	0.2208	0.2424	0.2661
1974	Sub CTW	0.0082	0.0158	0.0344	0.0118	0.0450	0.1190	0.0147	0.0855	0.2657
1974	DuPont CTW	0.0263	0.0355	0.0478	0.0881	0.1152	0.1442	0.1859	0.2452	0.3103
1974	CTW	0.0244	0.0326	0.0432	0.0812	0.1068	0.1348	0.1719	0.2288	0.2926
1974	nonCTW	0.0407	0.0472	0.0543	0.1144	0.1253	0.1362	0.2133	0.2351	0.2589

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1974	All Workers	0.0377	0.0429	0.0488	0.1117	0.1224	0.1329	0.2187	0.2402	0.2622
1975	Sub CTW	0.0117	0.0207	0.0373	0.0199	0.0498	0.0865	0.0275	0.0858	0.1581
1975	DuPont CTW	0.0263	0.0349	0.0463	0.0757	0.1030	0.1325	0.1469	0.2063	0.2704
1975	CTW	0.0253	0.0329	0.0429	0.0712	0.0958	0.1234	0.1370	0.1904	0.2489
1975	nonCTW	0.0409	0.0478	0.0555	0.1166	0.1279	0.1396	0.2153	0.2415	0.2701
1975	All Workers	0.0377	0.0433	0.0494	0.1103	0.1215	0.1323	0.2136	0.2361	0.2601
1976	Sub CTW	0.0088	0.0157	0.0281	0.0184	0.0408	0.0713	0.0288	0.0738	0.1405
1976	DuPont CTW	0.0244	0.0336	0.0456	0.0809	0.1067	0.1340	0.1695	0.2239	0.2851
1976	CTW	0.0223	0.0298	0.0394	0.0731	0.0955	0.1200	0.1533	0.2019	0.2571
1976	nonCTW	0.0398	0.0467	0.0545	0.1128	0.1243	0.1361	0.2072	0.2334	0.2638
1976	All Workers	0.0357	0.0412	0.0473	0.1072	0.1182	0.1292	0.2093	0.2327	0.2592
1977	Sub CTW	0.0112	0.0163	0.0235	0.0256	0.0405	0.0595	0.0423	0.0727	0.1140
1977	DuPont CTW	0.0225	0.0323	0.0454	0.0823	0.1118	0.1411	0.1834	0.2480	0.3104
1977	CTW	0.0197	0.0260	0.0341	0.0655	0.0865	0.1099	0.1386	0.1881	0.2417
1977	nonCTW	0.0463	0.0536	0.0613	0.1161	0.1271	0.1390	0.1960	0.2220	0.2512
1977	All Workers	0.0370	0.0425	0.0486	0.1086	0.1196	0.1306	0.2094	0.2325	0.2571
1978	Sub CTW	0.0087	0.0123	0.0176	0.0184	0.0294	0.0429	0.0293	0.0514	0.0789
1978	DuPont CTW	0.0335	0.0456	0.0599	0.0878	0.1067	0.1256	0.1442	0.1844	0.2317
1978	CTW	0.0210	0.0277	0.0363	0.0630	0.0811	0.0995	0.1247	0.1612	0.2000
1978	nonCTW	0.0417	0.0485	0.0560	0.1092	0.1179	0.1264	0.1890	0.2092	0.2306
1978	All Workers	0.0363	0.0416	0.0476	0.1016	0.1102	0.1184	0.1900	0.2062	0.2236
1979	Sub CTW	0.0118	0.0170	0.0241	0.0265	0.0389	0.0537	0.0424	0.0661	0.0964
1979	DuPont CTW	0.0283	0.0400	0.0540	0.0786	0.1001	0.1257	0.1312	0.1814	0.2472
1979	CTW	0.0223	0.0293	0.0379	0.0627	0.0796	0.0991	0.1152	0.1511	0.1977
1979	nonCTW	0.0402	0.0470	0.0543	0.1085	0.1183	0.1285	0.1905	0.2147	0.2411
1979	All Workers	0.0362	0.0417	0.0475	0.1007	0.1100	0.1194	0.1853	0.2056	0.2275



Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1980	Sub CTW	0.0105	0.0145	0.0200	0.0227	0.0343	0.0480	0.0368	0.0598	0.0874
1980	DuPont CTW	0.0253	0.0352	0.0476	0.0717	0.0897	0.1091	0.1272	0.1630	0.2099
1980	CTW	0.0187	0.0241	0.0311	0.0521	0.0668	0.0827	0.0990	0.1284	0.1615
1980	nonCTW	0.0431	0.0493	0.0558	0.0994	0.1079	0.1168	0.1595	0.1787	0.2003
1980	All Workers	0.0351	0.0399	0.0450	0.0911	0.0993	0.1075	0.1624	0.1787	0.1967
1981	Sub CTW	0.0098	0.0124	0.0157	0.0225	0.0306	0.0406	0.0379	0.0548	0.0763
1981	DuPont CTW	0.0177	0.0243	0.0328	0.0482	0.0643	0.0816	0.0874	0.1201	0.1580
1981	CTW	0.0133	0.0164	0.0200	0.0353	0.0444	0.0547	0.0648	0.0844	0.1069
1981	nonCTW	0.0268	0.0307	0.0351	0.0647	0.0727	0.0814	0.1099	0.1266	0.1456
1981	All Workers	0.0216	0.0244	0.0274	0.0572	0.0639	0.0708	0.1050	0.1190	0.1339
1982	Sub CTW	0.0095	0.0118	0.0144	0.0199	0.0251	0.0309	0.0315	0.0410	0.0517
1982	DuPont CTW	0.0146	0.0205	0.0281	0.0452	0.0612	0.0802	0.0894	0.1233	0.1703
1982	CTW	0.0125	0.0153	0.0186	0.0331	0.0412	0.0507	0.0605	0.0778	0.0999
1982	nonCTW	0.0235	0.0269	0.0305	0.0581	0.0636	0.0697	0.0978	0.1109	0.1257
1982	All Workers	0.0197	0.0221	0.0248	0.0521	0.0573	0.0627	0.0948	0.1057	0.1181
1983	Sub CTW	0.0091	0.0113	0.0140	0.0214	0.0266	0.0322	0.0360	0.0461	0.0570
1983	DuPont CTW	0.0189	0.0241	0.0298	0.0402	0.0476	0.0552	0.0586	0.0735	0.0931
1983	CTW	0.0128	0.0153	0.0181	0.0317	0.0368	0.0420	0.0548	0.0648	0.0752
1983	nonCTW	0.0198	0.0225	0.0256	0.0479	0.0528	0.0581	0.0815	0.0913	0.1027
1983	All Workers	0.0176	0.0196	0.0218	0.0436	0.0475	0.0516	0.0764	0.0841	0.0926
1984	Sub CTW	0.0083	0.0110	0.0145	0.0238	0.0309	0.0385	0.0450	0.0599	0.0758
1984	DuPont CTW	0.0198	0.0252	0.0315	0.0412	0.0510	0.0621	0.0619	0.0803	0.1026
1984	CTW	0.0123	0.0153	0.0187	0.0343	0.0413	0.0484	0.0640	0.0783	0.0941
1984	nonCTW	0.0199	0.0228	0.0261	0.0505	0.0560	0.0617	0.0886	0.0998	0.1119
1984	All Workers	0.0176	0.0199	0.0223	0.0470	0.0516	0.0562	0.0858	0.0952	0.1054
1985	Sub CTW	0.0085	0.0117	0.0157	0.0212	0.0294	0.0372	0.0372	0.0530	0.0677

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1985	DuPont CTW	0.0182	0.0235	0.0301	0.0347	0.0449	0.0561	0.0506	0.0681	0.0883
1985	CTW	0.0126	0.0158	0.0196	0.0311	0.0381	0.0455	0.0540	0.0670	0.0817
1985	nonCTW	0.0215	0.0246	0.0280	0.0485	0.0532	0.0583	0.0772	0.0874	0.0988
1985	All Workers	0.0191	0.0216	0.0241	0.0453	0.0494	0.0537	0.0761	0.0845	0.0937
1986	Sub CTW	0.0042	0.0060	0.0084	0.0119	0.0179	0.0255	0.0227	0.0362	0.0549
1986	DuPont CTW	0.0047	0.0073	0.0114	0.0142	0.0236	0.0363	0.0278	0.0500	0.0817
1986	CTW	0.0049	0.0065	0.0086	0.0148	0.0203	0.0269	0.0293	0.0423	0.0588
1986	nonCTW	0.0068	0.0084	0.0102	0.0225	0.0276	0.0335	0.0468	0.0596	0.0750
1986	All Workers	0.0066	0.0077	0.0091	0.0215	0.0253	0.0299	0.0447	0.0543	0.0660
1987	Sub CTW	0.0040	0.0059	0.0089	0.0110	0.0184	0.0282	0.0207	0.0382	0.0624
1987	DuPont CTW	0.0053	0.0080	0.0123	0.0142	0.0231	0.0359	0.0253	0.0457	0.0768
1987	CTW	0.0050	0.0068	0.0091	0.0146	0.0209	0.0284	0.0283	0.0432	0.0616
1987	nonCTW	0.0067	0.0082	0.0099	0.0196	0.0249	0.0313	0.0381	0.0510	0.0669
1987	All Workers	0.0066	0.0077	0.0091	0.0194	0.0237	0.0287	0.0386	0.0490	0.0612
1988	Sub CTW	0.0032	0.0049	0.0077	0.0094	0.0171	0.0309	0.0184	0.0386	0.0804
1988	DuPont CTW	0.0068	0.0112	0.0177	0.0169	0.0275	0.0389	0.0275	0.0486	0.0740
1988	CTW	0.0044	0.0064	0.0091	0.0142	0.0219	0.0329	0.0290	0.0483	0.0784
1988	nonCTW	0.0064	0.0076	0.0092	0.0167	0.0205	0.0252	0.0297	0.0388	0.0503
1988	All Workers	0.0062	0.0073	0.0085	0.0176	0.0212	0.0256	0.0336	0.0424	0.0537
1989	Sub CTW	0.0030	0.0041	0.0056	0.0087	0.0128	0.0186	0.0169	0.0270	0.0417
1989	DuPont CTW	0.0032	0.0048	0.0073	0.0072	0.0120	0.0202	0.0112	0.0218	0.0425
1989	CTW	0.0033	0.0043	0.0055	0.0094	0.0128	0.0173	0.0179	0.0260	0.0376
1989	nonCTW	0.0049	0.0059	0.0070	0.0136	0.0162	0.0193	0.0253	0.0314	0.0385
1989	All Workers	0.0046	0.0053	0.0061	0.0130	0.0152	0.0178	0.0251	0.0302	0.0363
1990	Sub CTW	0.0049	0.0062	0.0077	0.0125	0.0159	0.0201	0.0220	0.0293	0.0391
1990	DuPont CTW	0.0035	0.0052	0.0077	0.0068	0.0118	0.0193	0.0100	0.0200	0.0363

Year	Group	GM Lower	GM Estimate	GM Upper	84th Lower	84th Estimate	84th Upper	95th Lower	95th Estimate	95th Upper
1990	CTW	0.0049	0.0059	0.0072	0.0121	0.0151	0.0187	0.0211	0.0275	0.0357
1990	nonCTW	0.0047	0.0056	0.0066	0.0126	0.0153	0.0185	0.0233	0.0295	0.0371
1990	All Workers	0.0050	0.0057	0.0065	0.0132	0.0153	0.0177	0.0243	0.0289	0.0344

a. There were too few CTWs in 1954 to substratify into Sub CTW and DuPont CTW.