

Appendix A Implementation details for Algorithm 1

Root-finding Strategy for the Threshold θ

To find θ , we need to solve Eq. (2). In practice, the function can be highly non-linear and may exhibit multiple roots. To ensure a robust solution, we implement a two-stage strategy to ensure a robust solution. First, a global grid search is performed to identify sub-intervals where a sign change occurs, effectively localizing all potential root candidates. Subsequently, function `unitroot()` in the R package *stats* is applied to find the roots in each sub-interval. Since analytical derivatives for the candidate distributions may be complex or unavailable, the derivatives f'_1 and f'_2 in Eq. (2) are computed using numerical differentiation. The R package *numDeriv* is used.

Initialization

Numerical estimation of composite distributions is often sensitive to initial values, which may lead general-purpose optimizers to converge toward local optima rather than the global maximum likelihood. To increase the chance of detecting the global optima, or at least a good solution, we implement an iterative, adaptive random initialization strategy proposed by Grün and Miljkovic [22]. The procedure is detailed as follows:

1. Proposal Generation: Starting from an initial feasible guess, new parameter candidates are generated via a random walk using independent normal distributions.
2. Adaptive Step Sizes: In our implementation, we employ different step sizes to account for the varying scales of the parameters: a step size of 1.5 is utilized for the GPD location parameter to ensure sufficient exploration of the tail threshold, while a smaller step size of 0.1 is applied to all other parameters to maintain local precision.
3. Feasibility via Winsorization: To ensure that all proposed parameter values remain within the theoretically valid range for their respective distributions, several replications of such proposals (set to 100 in our study) are generated using winsorization.
4. Selection and Acceptance: From the generated replications, the candidate that maximizes the log-likelihood is identified. Following the logic of stochastic search, this new proposal is accepted as the starting point for the subsequent iteration with a probability equal to the exponential of the difference between the new and current log-likelihood values.
5. Iteration: This scheme is repeated for 100 iterations to identify a good solution that serves as a robust starting point for the final general-purpose optimizer.

Appendix B Overview of Copula Functions

To model the dependence structure between the marginal distributions of SBP and DBP, we employ three widely used bivariate copulas. Each copula captures different types of dependence characteristics.

Gaussian Copula: The Gaussian copula is a member of the elliptical family and is constructed from the bivariate

normal distribution. It is defined as:

$$C_{Ga}(u, v|\rho) = \Phi_\rho(\Phi^{-1}(u), \Phi^{-1}(v)),$$

where Φ^{-1} is the inverse cumulative distribution function of a standard normal distribution and Φ_ρ is the joint CDF of a bivariate normal distribution with correlation coefficient $\rho \in [-1, 1]$. The Gaussian copula is symmetric and assumes zero tail dependence, which means it does not capture extreme co-movements in the very high or very low values.

Gumbel Copula: The Gumbel copula is an asymmetric Archimedean copula defined by the generator function $\phi(t) = (-\ln t)^\alpha$. Its distribution function is:

$$C_{Gu}(u, v|\alpha) = \exp\left(-[(-\ln u)^\alpha + (-\ln v)^\alpha]^{1/\alpha}\right),$$

where the association parameter $\alpha \geq 1$. The Gumbel copula is characterized by upper tail dependence. In the context of blood pressure, this implies that extreme hypertensive values of SBP are likely to occur simultaneously with extreme values of DBP.

Clayton Copula: The Clayton copula is another Archimedean copula, defined by the generator $\phi(t) = \frac{1}{\alpha}(t^{-\alpha} - 1)$. Its distribution function is:

$$C_{Cl}(u, v|\alpha) = (u^{-\alpha} + v^{-\alpha} - 1)^{-1/\alpha},$$

where $\alpha > 0$. The Clayton copula exhibits lower tail dependence. This structure suggests a stronger correlation between SBP and DBP when values are low, with the dependence becoming weaker as values increase.

Appendix C Parameter estimation for marginal distribution (2011–2013, 2016–2018)

Table S1: Estimated Parameters of the Lognormal-GPD Composite Distribution (Part 1: ≤ 29 , 30–39, and 40–49, 2011–2013)

Age Group	Gender	Type	θ	ϕ	μ_1	σ_1	μ_2	σ_2	ξ
≤ 29	Female	SBP	139.5605	0.0038	4.6940	0.0943	139.5535	3.6253	0.2340
			–	–	(0.0024)	(0.0022)	(0.0000)	(1.4249)	(0.6451)
	DBP		90.2109	0.0049	4.2073	0.1244	90.2064	2.2510	0.3129
			–	–	(0.0031)	(0.0027)	(0.0000)	(0.7598)	(0.5680)
	Male	SBP	155.4678	0.0068	4.7876	0.0966	155.4639	9.1949	–0.3371
			–	–	(0.0021)	(0.0016)	(0.0000)	(2.0396)	(0.1852)
30–39	Female	SBP	140.2313	0.0109	4.7132	0.0995	140.2242	5.4698	0.4324
			–	–	(0.0017)	(0.0014)	(0.0000)	(0.7720)	(0.2010)
	DBP		93.6006	0.0105	4.2289	0.1291	93.5818	5.6532	0.1858
			–	–	(0.0020)	(0.0015)	(0.0000)	(0.6326)	(0.1216)
	Male	SBP	148.5549	0.0290	4.8072	0.0959	140.9291	6.5955	0.1576
			–	–	(0.0016)	(0.0012)	(0.0016)	(0.3387)	(0.0500)
40–49	Female	SBP	142.5780	0.0469	4.7555	0.1103	142.5744	9.9750	0.0646
			–	–	(0.0019)	(0.0015)	(0.0000)	(0.7401)	(0.0762)
	DBP		88.7668	0.0947	4.2837	0.1416	88.7228	7.6495	–0.0448
			–	–	(0.0027)	(0.0021)	(0.0000)	(0.4249)	(0.0456)
	Male	SBP	139.5382	0.1661	4.8241	0.1066	139.5311	9.4426	–0.0063
			–	–	(0.0005)	(0.0007)	(0.0000)	(0.1917)	(0.0230)
		DBP	119.5338	0.0030	4.3750	0.1453	101.2686	3.9574	0.1544
			–	–	(0.0020)	(0.0115)	(0.0000)	(0.6972)	(0.0016)

1. μ_1 and σ_1 are the parameters of the Lognormal component from Eq.(3); μ_2 , σ_2 , and ξ are the parameters of the GPD component from Eq.(4), $\hat{\theta}$ is solved from Eq.(2); $\hat{\phi}$ is calculated via Eq.(1).
2. Standard errors are reported in parentheses.

Table S2: Estimated Parameters of the Lognormal-GPD Composite Distribution (Part 2: 50–59, 60–69, and ≥ 70 , 2011–2013)

Age Group	Gender	Type	θ	ϕ	μ_1	σ_1	μ_2	σ_2	ξ
50–59	Female	SBP	140.6864	0.1556	4.8070	0.1220	140.6794	11.2535	−0.0700
			–	–	(0.0058)	(0.0042)	(0.0048)	(0.9023)	(0.0651)
		DBP	90.0524	0.1442	4.3335	0.1490	90.0479	7.8918	−0.1716
			–	–	(0.0036)	(0.0027)	(0.0000)	(0.3436)	(0.0319)
	Male	SBP	138.9413	0.2331	4.8356	0.1078	138.9343	10.8887	−0.0491
			–	–	(0.0028)	(0.0020)	(0.0011)	(0.3858)	(0.0276)
60–69	Female	SBP	144.4547	0.2350	4.8607	0.1238	144.4474	13.0041	−0.1967
			–	–	(0.0090)	(0.0061)	(0.0118)	(1.0584)	(0.0517)
		DBP	92.7451	0.1458	4.3829	0.1474	92.7404	6.9030	−0.1324
			–	–	(0.0058)	(0.0042)	(0.0000)	(0.4270)	(0.0403)
	Male	SBP	143.9141	0.2365	4.8700	0.1138	143.9068	11.4733	−0.0581
			–	–	(0.0045)	(0.0033)	(0.0044)	(0.6590)	(0.0465)
≥ 70	Female	SBP	140.5412	0.7670	4.9429	0.1289	140.5341	17.7073	−0.2488
			–	–	(0.0048)	(0.0036)	(0.3022)	(3.5564)	(0.2008)
		DBP	86.9701	0.4354	4.4123	0.1478	86.9658	9.5910	−0.1215
			–	–	(0.0134)	(0.0085)	(0.0011)	(0.7148)	(0.0566)
	Male	SBP	151.3275	0.2561	4.9109	0.1204	149.7078	14.6596	−0.1957
			–	–	(0.0048)	(0.0035)	(0.0000)	(4.1396)	(0.0315)
≥ 70	Male	DBP	87.6454	0.4160	4.4289	0.1413	87.6409	8.4567	−0.1182
			–	–	(0.0111)	(0.0061)	(0.0000)	(0.3982)	(0.0343)

1. μ_1 and σ_1 are the parameters of the Lognormal component from Eq.(3); μ_2, σ_2 , and ξ are the parameters of the GPD component from Eq.(4), $\hat{\theta}$ is solved from Eq.(2); $\hat{\phi}$ is calculated via Eq.(1).
2. Standard errors are provided in parentheses.

Table S3: Estimated Parameters of the Lognormal-GPD Composite Distribution (Part 1: ≤ 29 , 30–39, and 40–49, 2016–2018)

Age Group	Gender	Type	θ	ϕ	μ_1	σ_1	μ_2	σ_2	ξ
≤ 29	Female	SBP	143.7170	0.0056	4.7153	0.0958	131.7963	3.3777	0.2415
			–	–	(0.0016)	(0.0011)	(0.0007)	(2.5227)	(0.2836)
	DBP		93.6641	0.0080	4.2221	0.1289	78.6594	3.8689	0.0763
			–	–	(0.0021)	(0.0015)	(0.0000)	(1.6702)	(0.2379)
	Male	SBP	141.3161	0.0729	4.7989	0.0962	138.1874	8.1493	0.0074
			–	–	(0.0015)	(0.0011)	(0.0000)	(0.9863)	(0.0543)
30–39	Female	SBP	129.2671	0.0838	4.7157	0.0950	129.2541	7.9024	0.0211
			–	–	(0.0007)	(0.0005)	(0.0000)	(0.2611)	(0.0257)
	DBP		81.3513	0.1084	4.2258	0.1251	81.1408	6.5995	–0.0224
			–	–	(0.0009)	(0.0007)	(0.0000)	(0.2072)	(0.0209)
	Male	SBP	142.6045	0.0781	4.8087	0.0959	139.0127	8.5100	0.0762
			–	–	(0.0007)	(0.0005)	(0.0000)	(0.4100)	(0.0276)
40–49	Female	SBP	133.3377	0.1296	4.7504	0.1050	133.3243	10.4222	–0.0333
			–	–	(0.0008)	(0.0006)	(0.0063)	(0.3290)	(0.0287)
	DBP		84.4085	0.1280	4.2583	0.1369	84.2250	7.7535	–0.0400
			–	–	(0.0010)	(0.0007)	(0.0000)	(0.2391)	(0.0207)
	Male	SBP	145.6488	0.0906	4.8131	0.0940	145.6451	14.8211	–0.0285
			–	–	(0.0008)	(0.0005)	(0.0048)	(0.4068)	(0.0251)
		DBP	94.5929	0.1162	4.3606	0.1422	92.5202	8.7215	–0.0603
			–	–	(0.0010)	(0.0007)	(0.0049)	(0.2844)	(0.0203)

1. μ_1 and σ_1 are the parameters of the Lognormal component from Eq.(3); μ_2 , σ_2 , and ξ are the parameters of the GPD component from Eq.(4), $\hat{\theta}$ is solved from Eq.(2); $\hat{\phi}$ is calculated via Eq.(1).

2. Standard errors are reported in parentheses.

Table S4: Estimated Parameters of the Lognormal-GPD Composite Distribution (Part 2: 50–59, 60–69, and ≥ 70 , 2016–2018)

Age Group	Gender	Type	θ	ϕ	μ_1	σ_1	μ_2	σ_2	ξ
50–59	Female	SBP	142.7428	0.1438	4.8163	0.1182	142.5756	11.4742	−0.0875
			–	–	(0.0010)	(0.0007)	(0.0000)	(0.4260)	(0.0221)
		DBP	89.7987	0.1271	4.3279	0.1504	89.7942	7.0784	−0.0652
			–	–	(0.0012)	(0.0009)	(0.0045)	(0.2682)	(0.0302)
	Male	SBP	151.4150	0.0800	4.8477	0.1121	151.2186	10.4016	0.0114
			–	–	(0.0009)	(0.0006)	(0.0000)	(0.4621)	(0.0277)
60–69	Female	SBP	151.1791	0.1209	4.8659	0.1174	150.7013	11.3514	−0.0976
			–	–	(0.0014)	(0.0010)	(0.0000)	(0.6430)	(0.0358)
		DBP	102.6336	0.0283	4.3537	0.1415	93.4116	6.9172	−0.0048
			–	–	(0.0019)	(0.0013)	(0.0043)	(0.8490)	(0.0737)
	Male	SBP	160.4905	0.0490	4.8780	0.1149	153.7447	9.9238	−0.0026
			–	–	(0.0012)	(0.0008)	(0.0068)	(0.5253)	(0.0434)
≥ 70	Female	SBP	159.5567	0.1109	4.9194	0.1129	159.1001	11.4833	−0.0666
			–	–	(0.0018)	(0.0012)	(0.0000)	(0.8489)	(0.0420)
		DBP	96.6762	0.0738	4.3579	0.1159	96.6737	10.9379	−0.1184
			–	–	(0.0022)	(0.0015)	(0.0045)	(0.7548)	(0.0602)
	Male	SBP	161.8835	0.0928	4.9246	0.1129	161.6554	11.0516	−0.0645
			–	–	(0.0013)	(0.0009)	(0.0057)	(0.6271)	(0.0438)
		DBP	95.4587	0.1311	4.3976	0.1409	95.4539	7.4212	−0.0734
			–	–	(0.0016)	(0.0011)	(0.0038)	(0.1910)	(0.0219)

1. μ_1 and σ_1 are the parameters of the Lognormal component from Eq.(3); μ_2 , σ_2 , and ξ are the parameters of the GPD component from Eq.(4), $\hat{\theta}$ is solved from Eq.(2); $\hat{\phi}$ is calculated via Eq.(1).

2. Standard errors are reported in parentheses.

Appendix D Diagnostic plots (2011 - 2013, 2016–2018, 2021–2023)

Fig. S1: Diagnostic plots for SBP (part 1, 2011–2013)

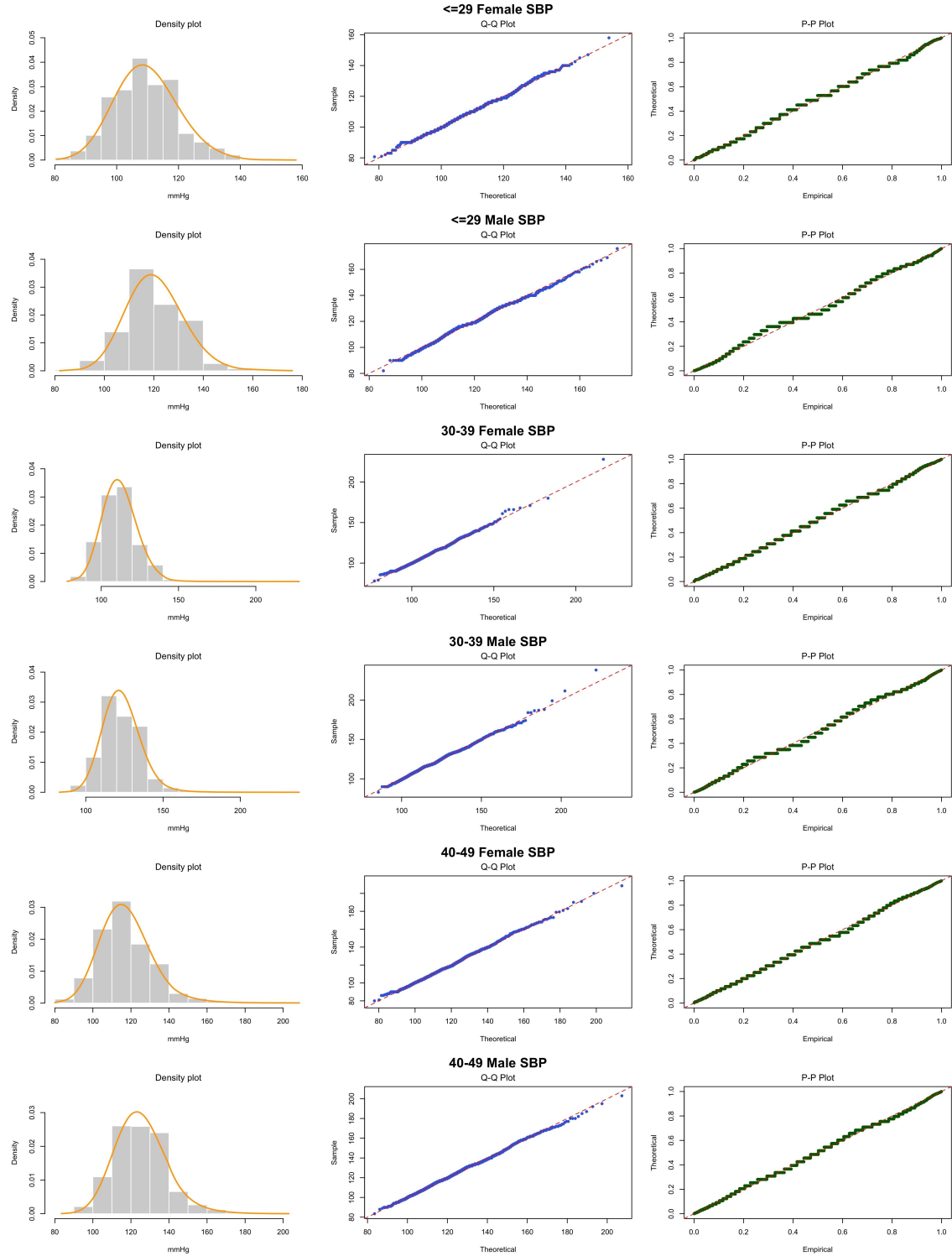


Fig. S2: Diagnostic plots for SBP (part 2, 2011–2013)

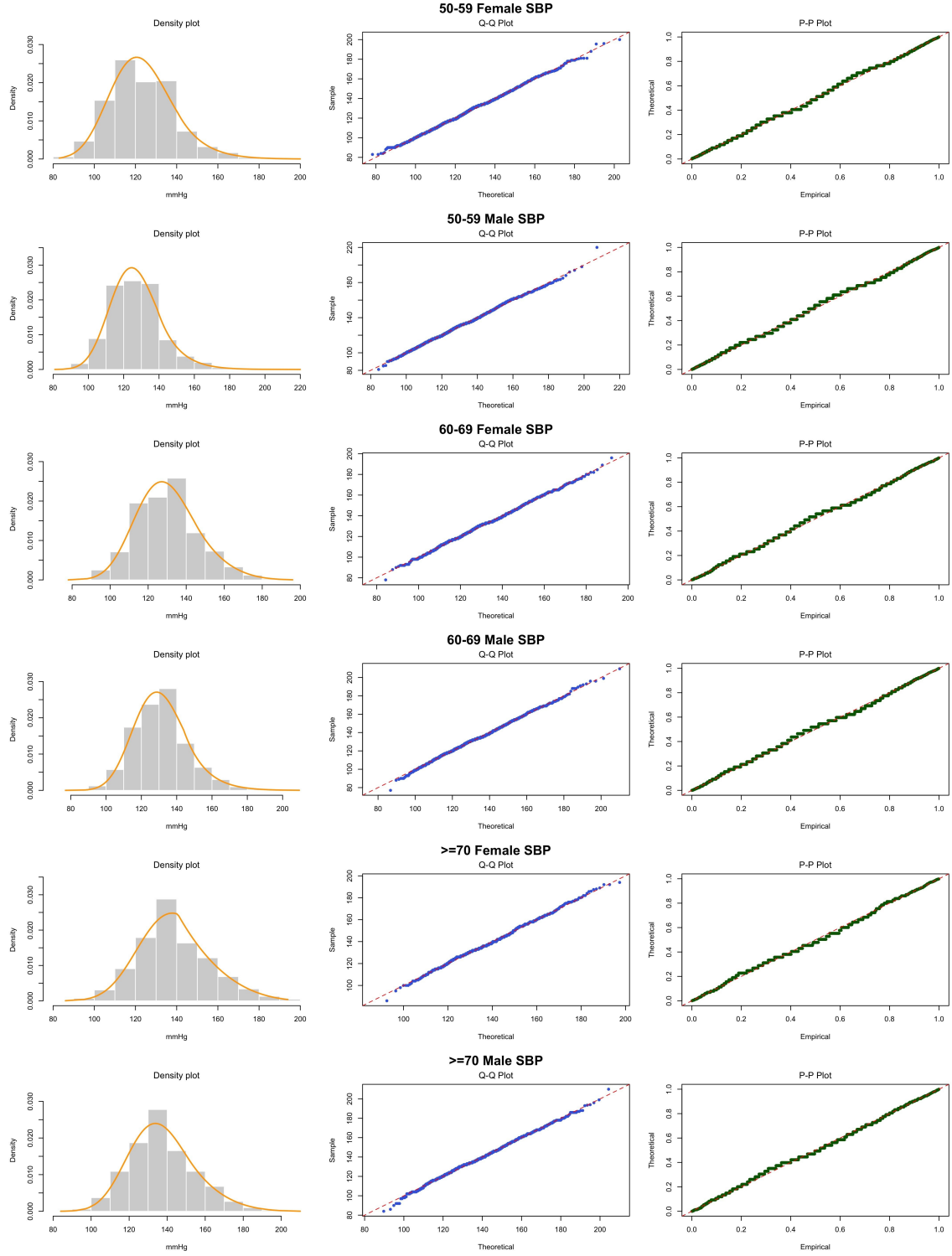


Fig. S3: Diagnostic plots for DBP (part 1, 2011–2013)

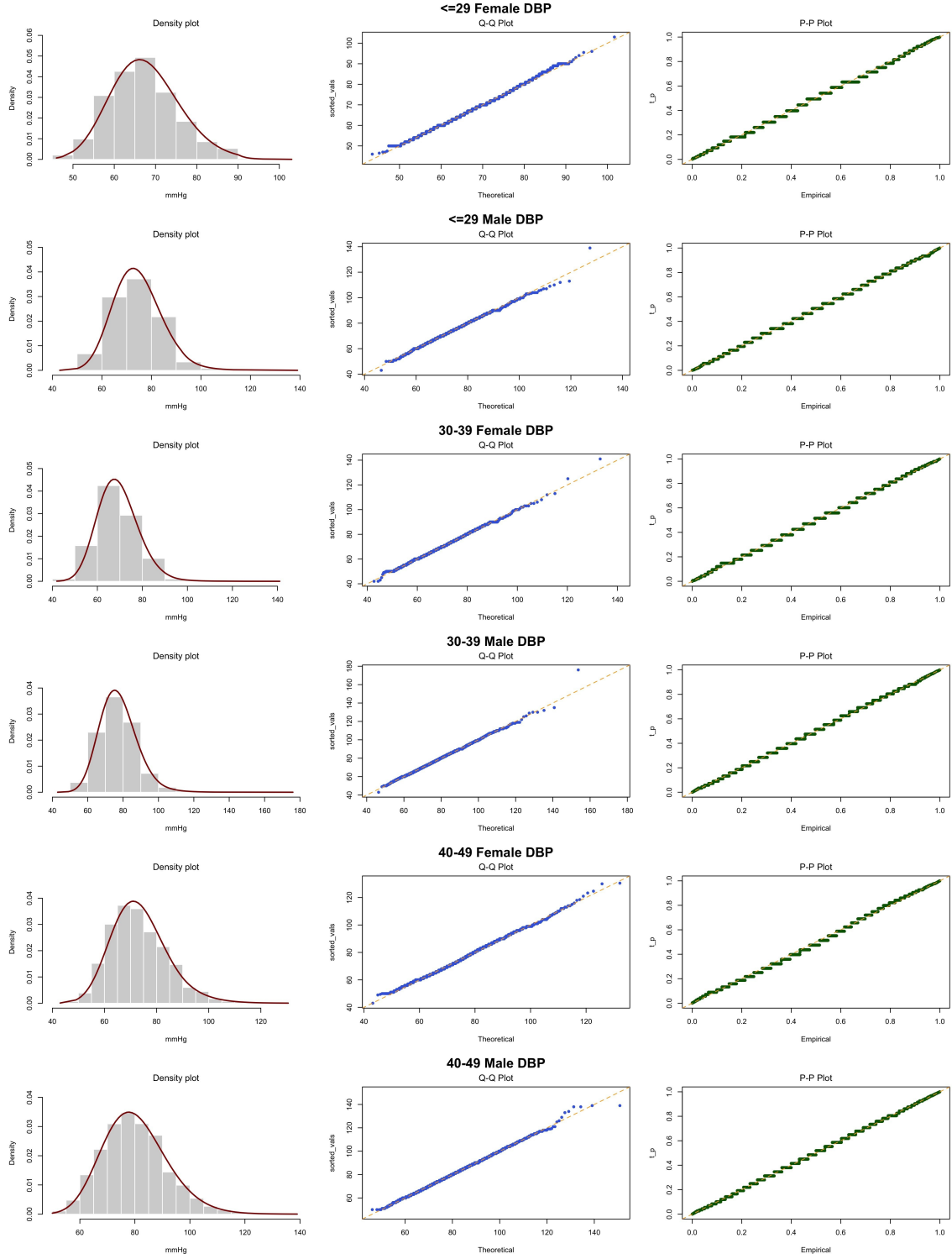


Fig. S4: Diagnostic plots for DBP (part 2, 2011–2013)

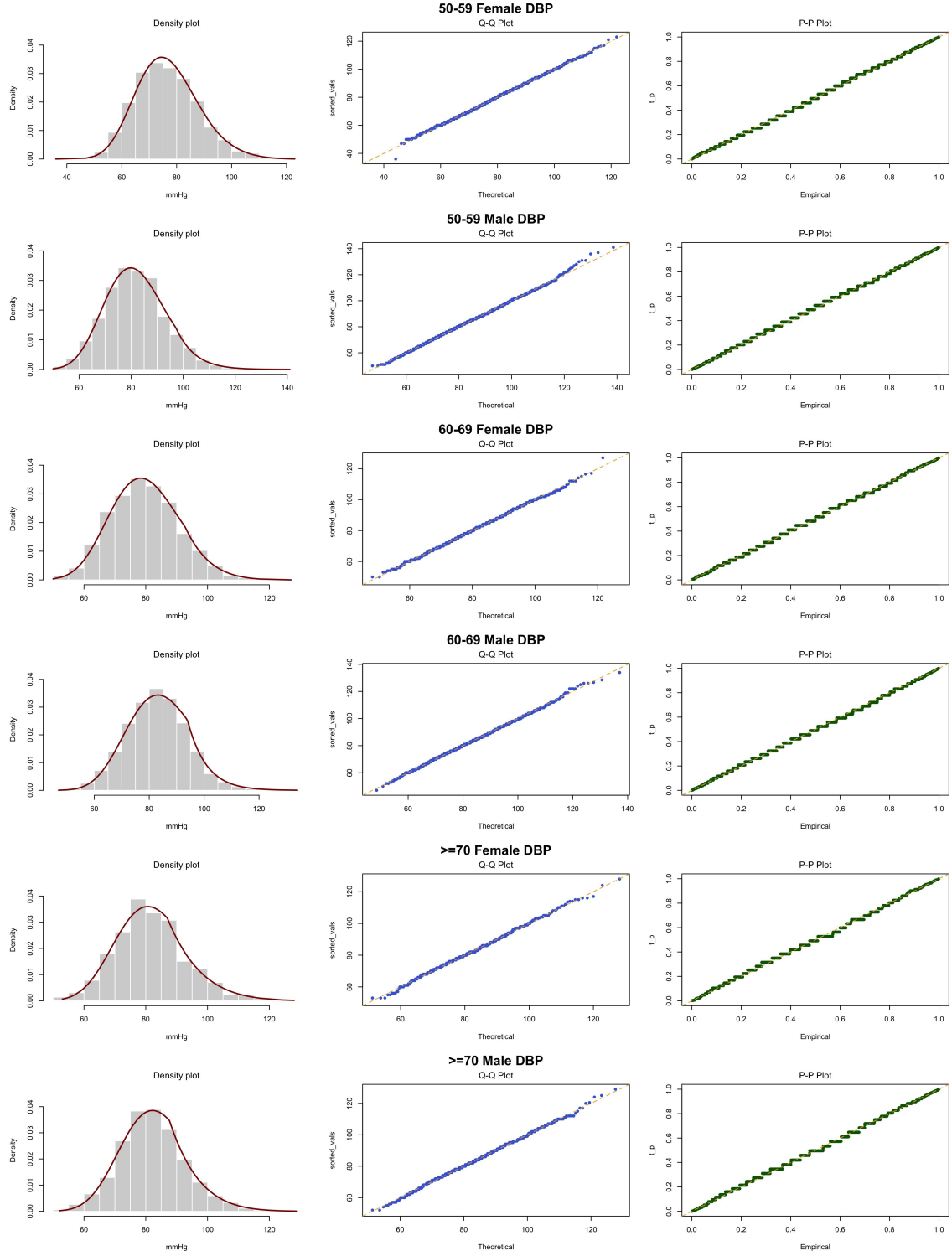


Fig. S5: Diagnostic plots for SBP (part 1, 2016–2018)

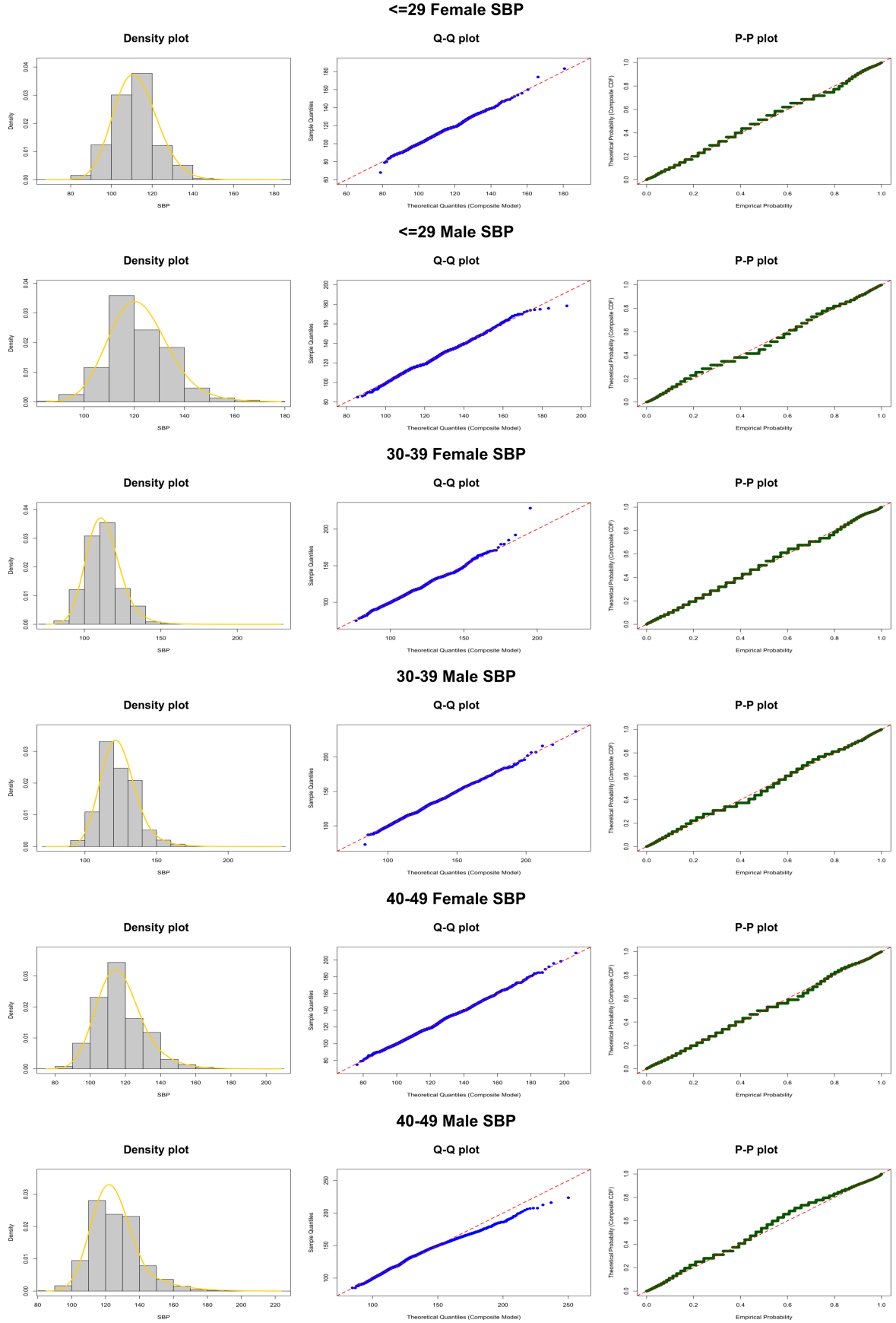


Fig. S6: Diagnostic plots for SBP (part 2, 2016–2018)

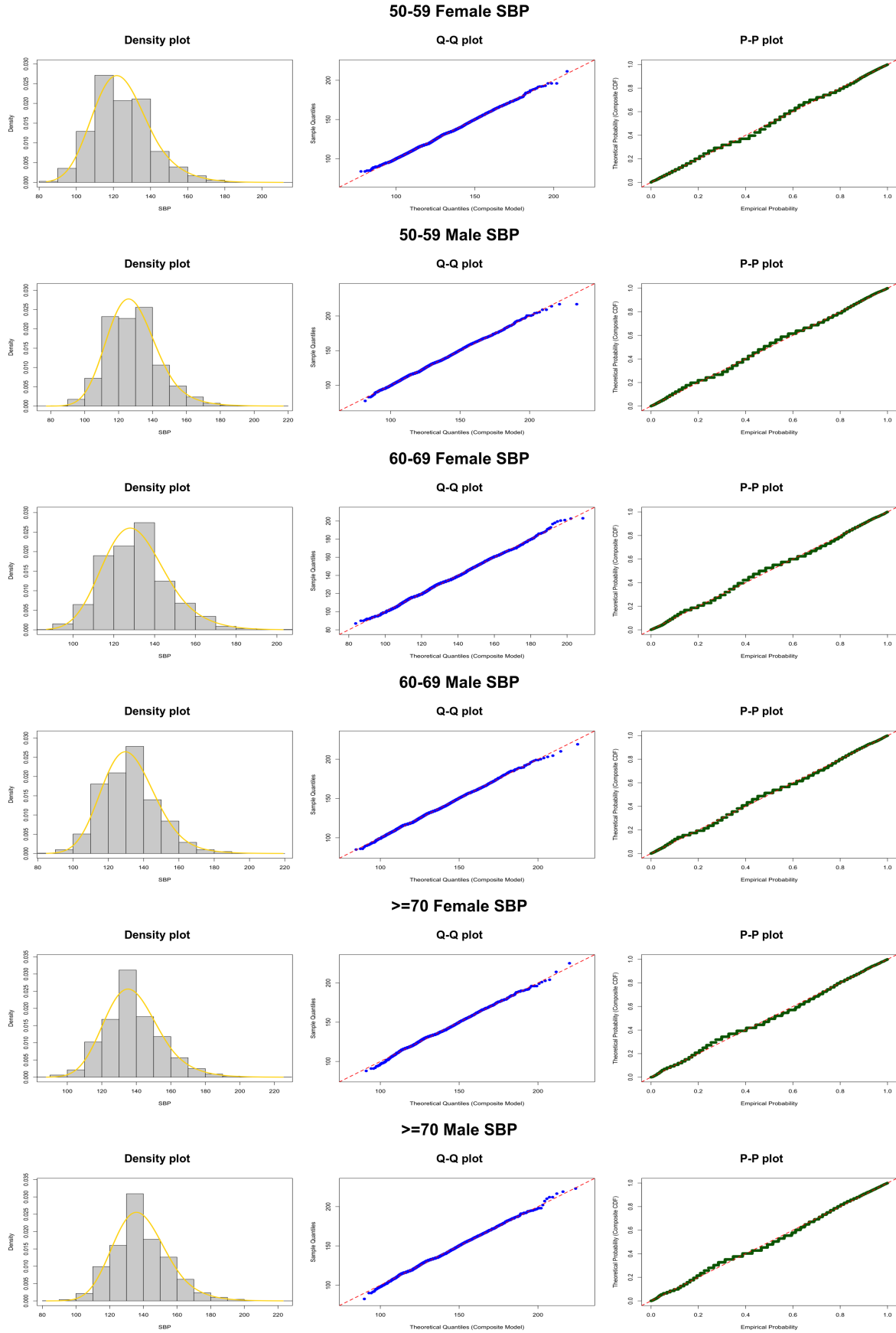


Fig. S7: Diagnostic plots for DBP (part 1, 2016–2018)

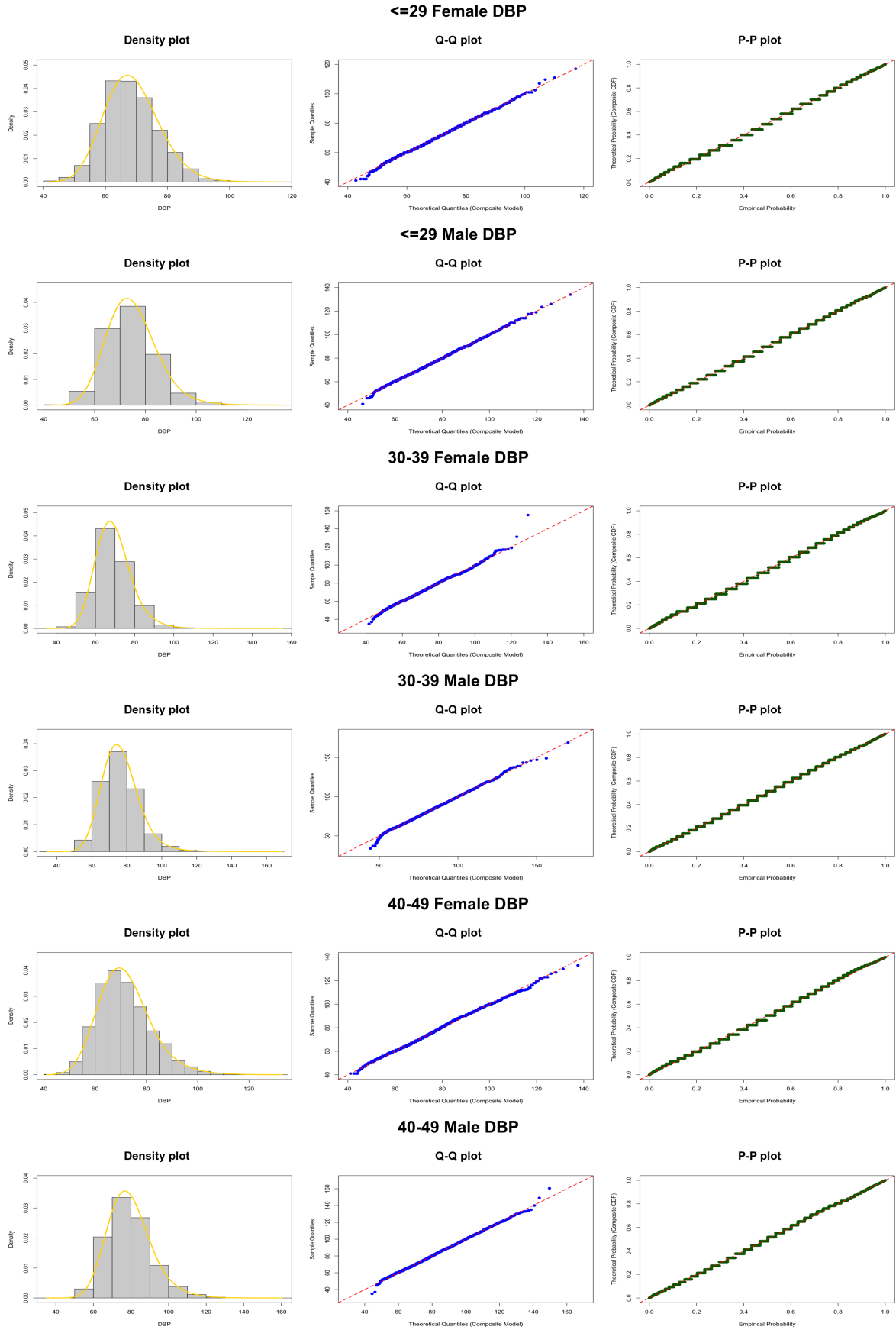


Fig. S8: Diagnostic plots for DBP (part 2, 2016–2018)

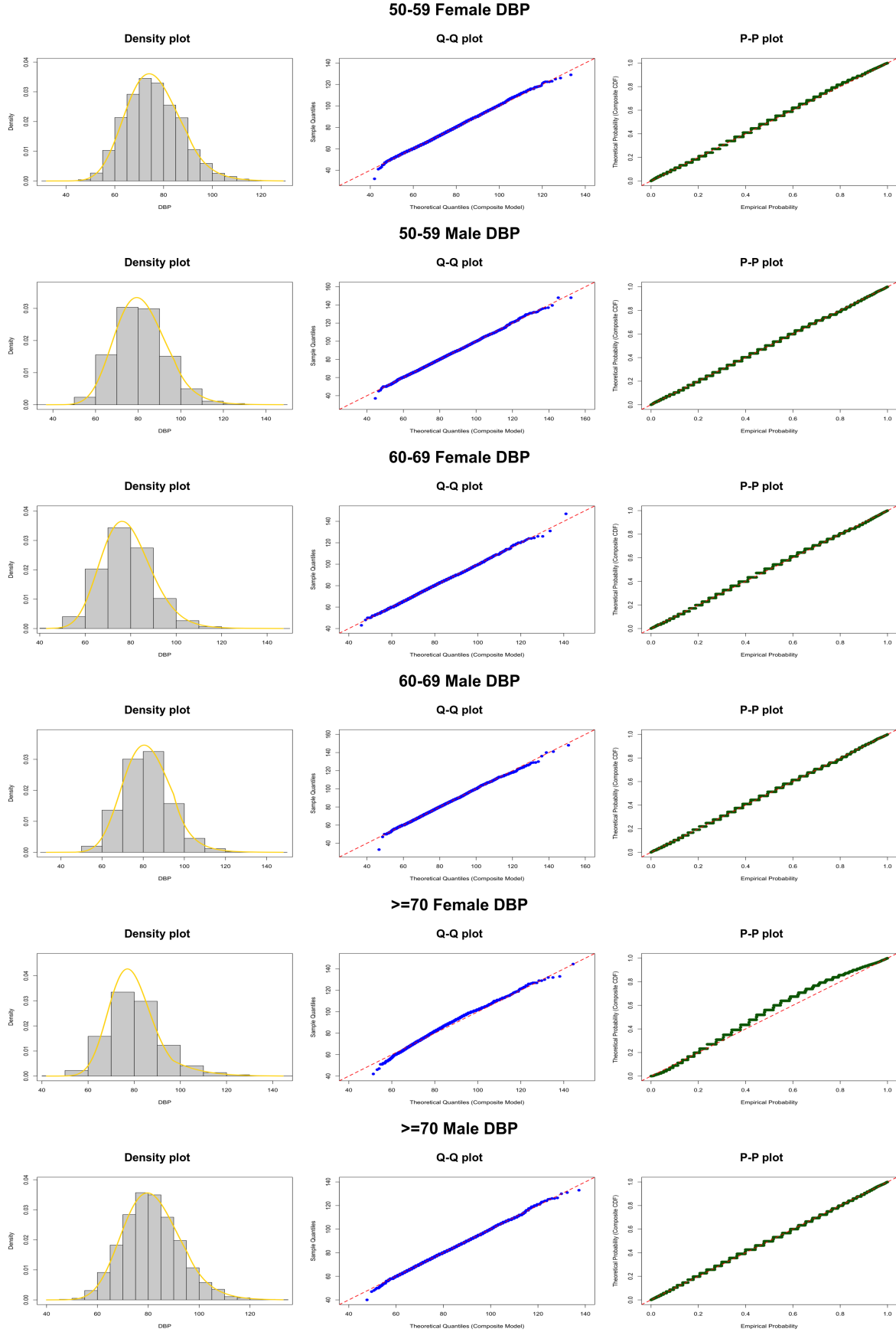


Fig. S9: Diagnostic plots for SBP (part 2, 2021–2023)

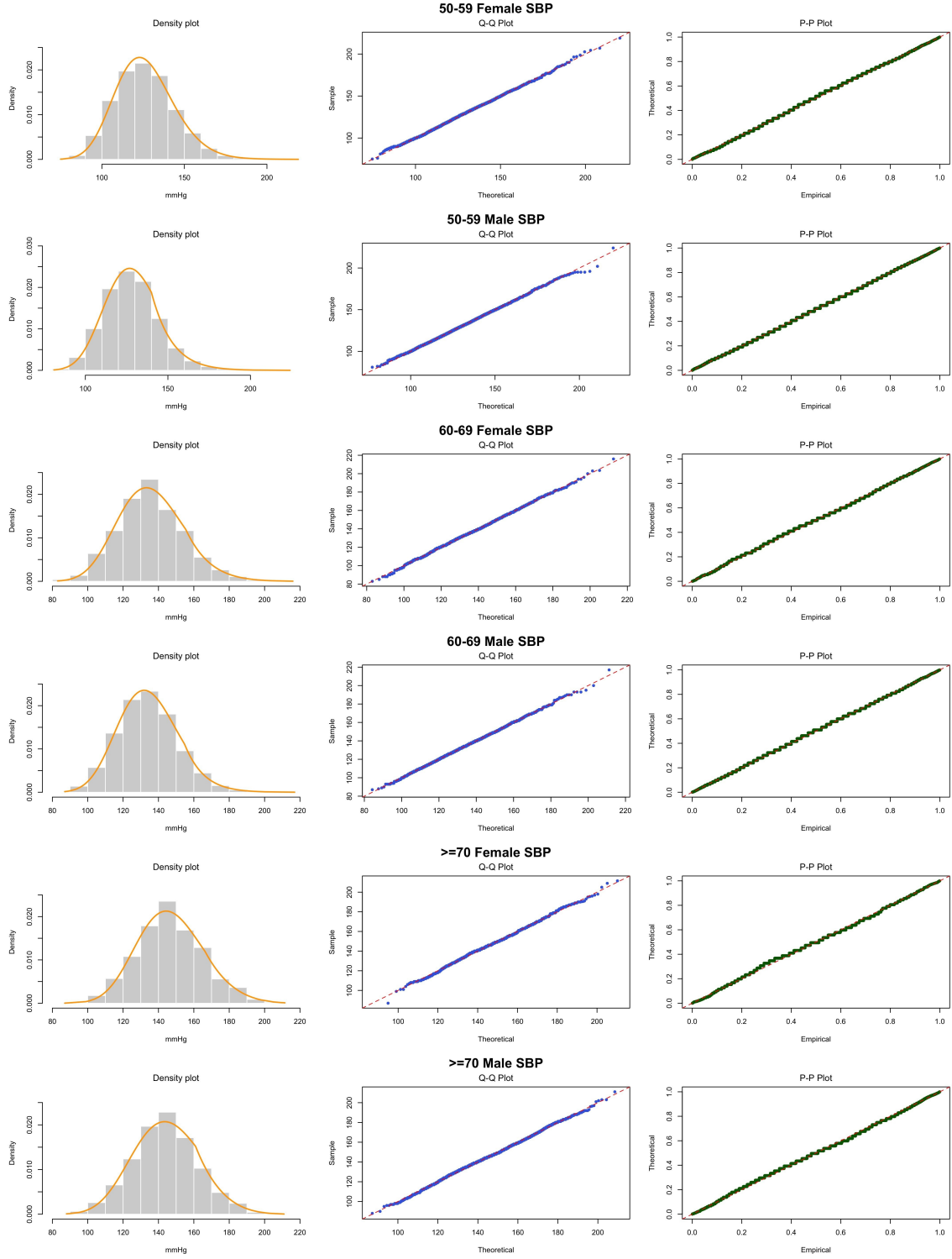


Fig. S10: Diagnostic plots for DBP (part 1, 2021–2023)

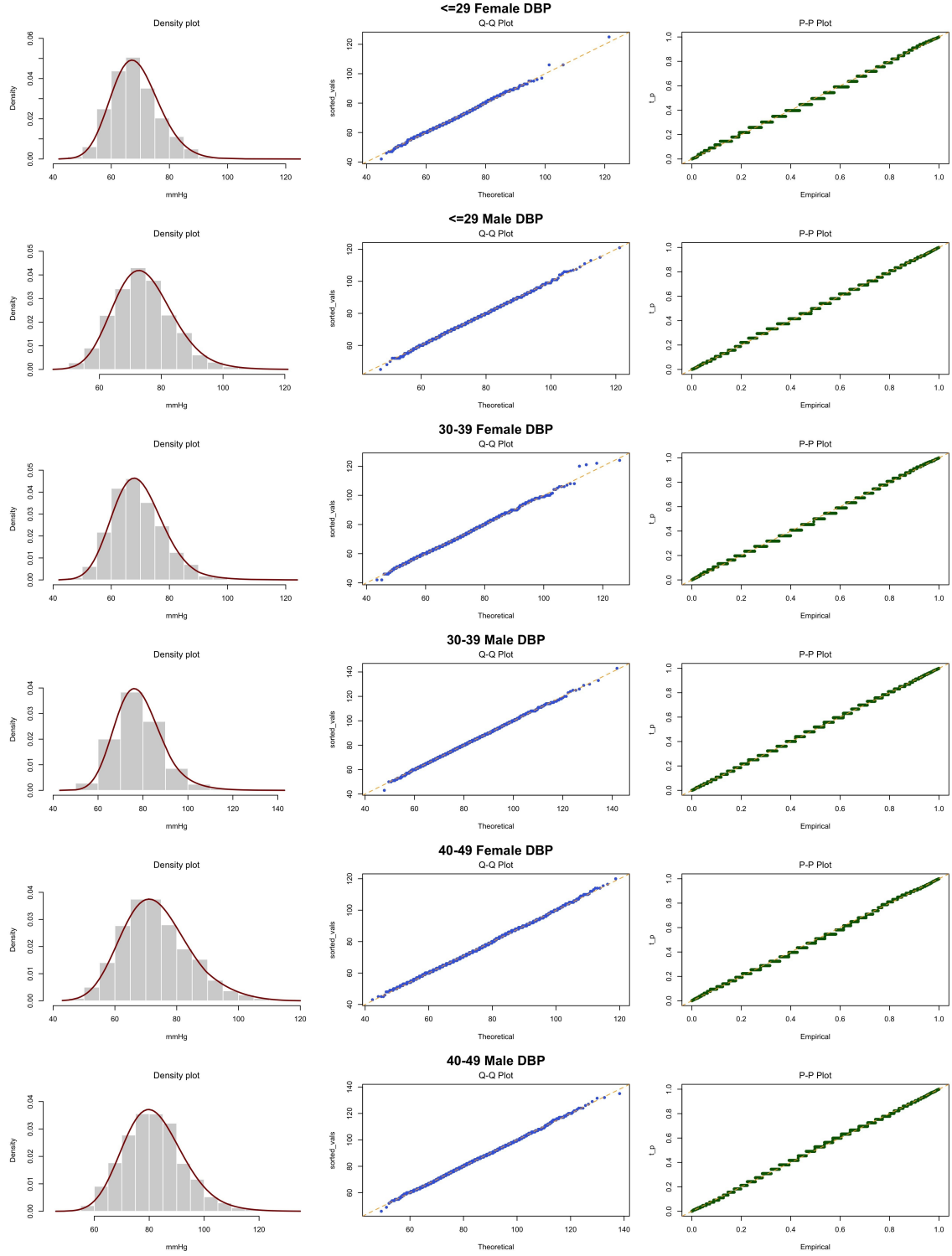


Fig. S11: Diagnostic plots for DBP (part 2, 2021–2023)

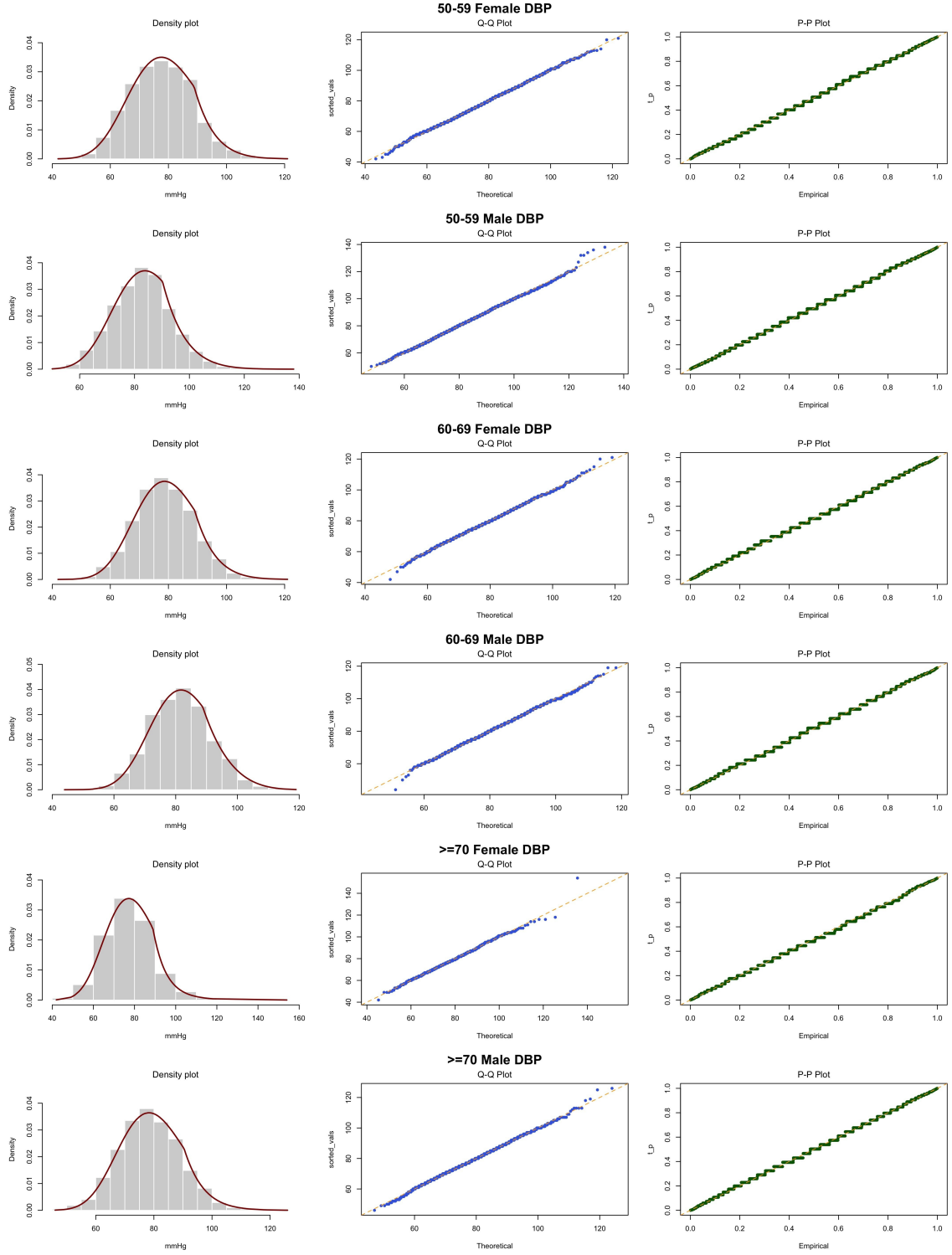
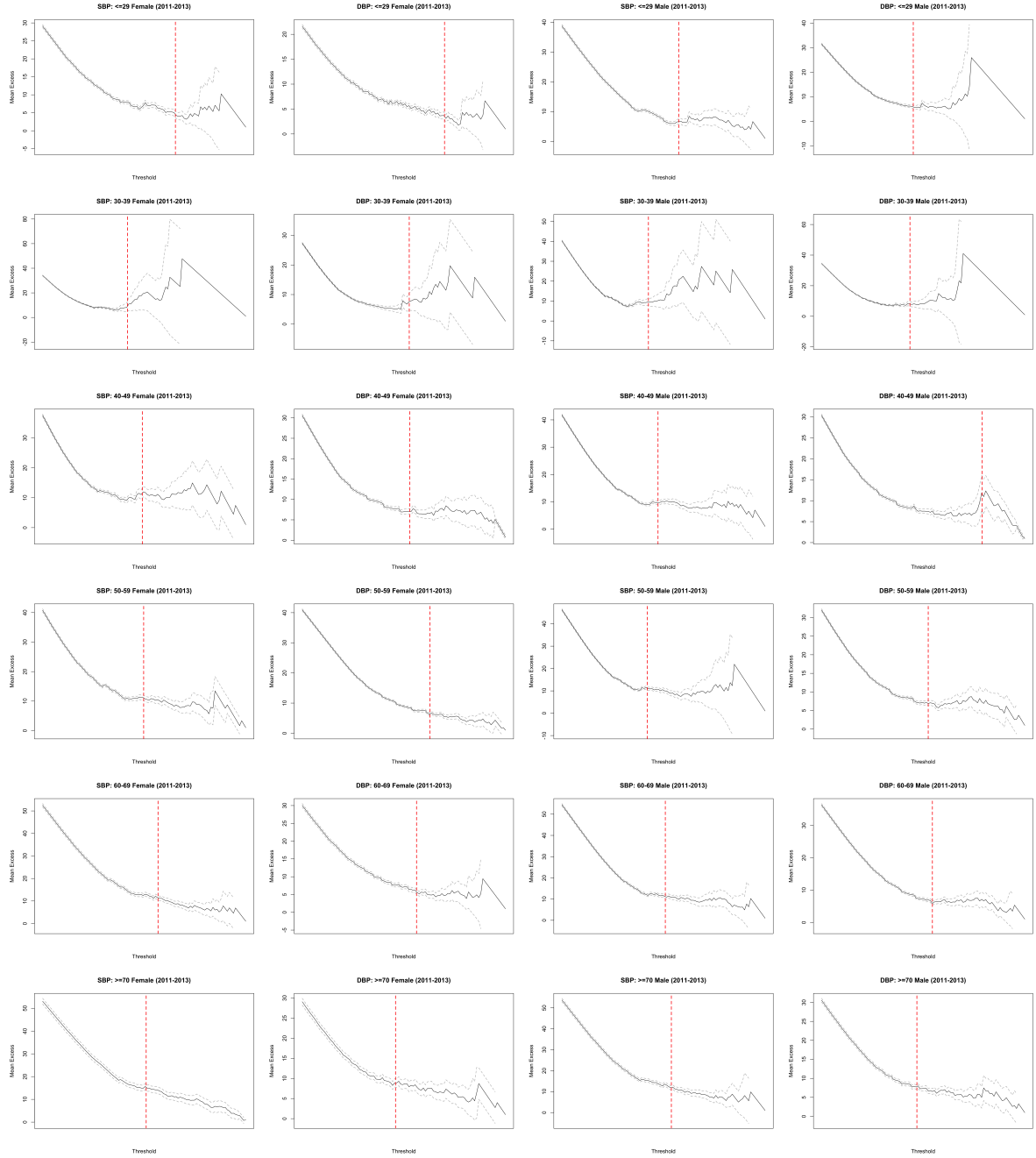
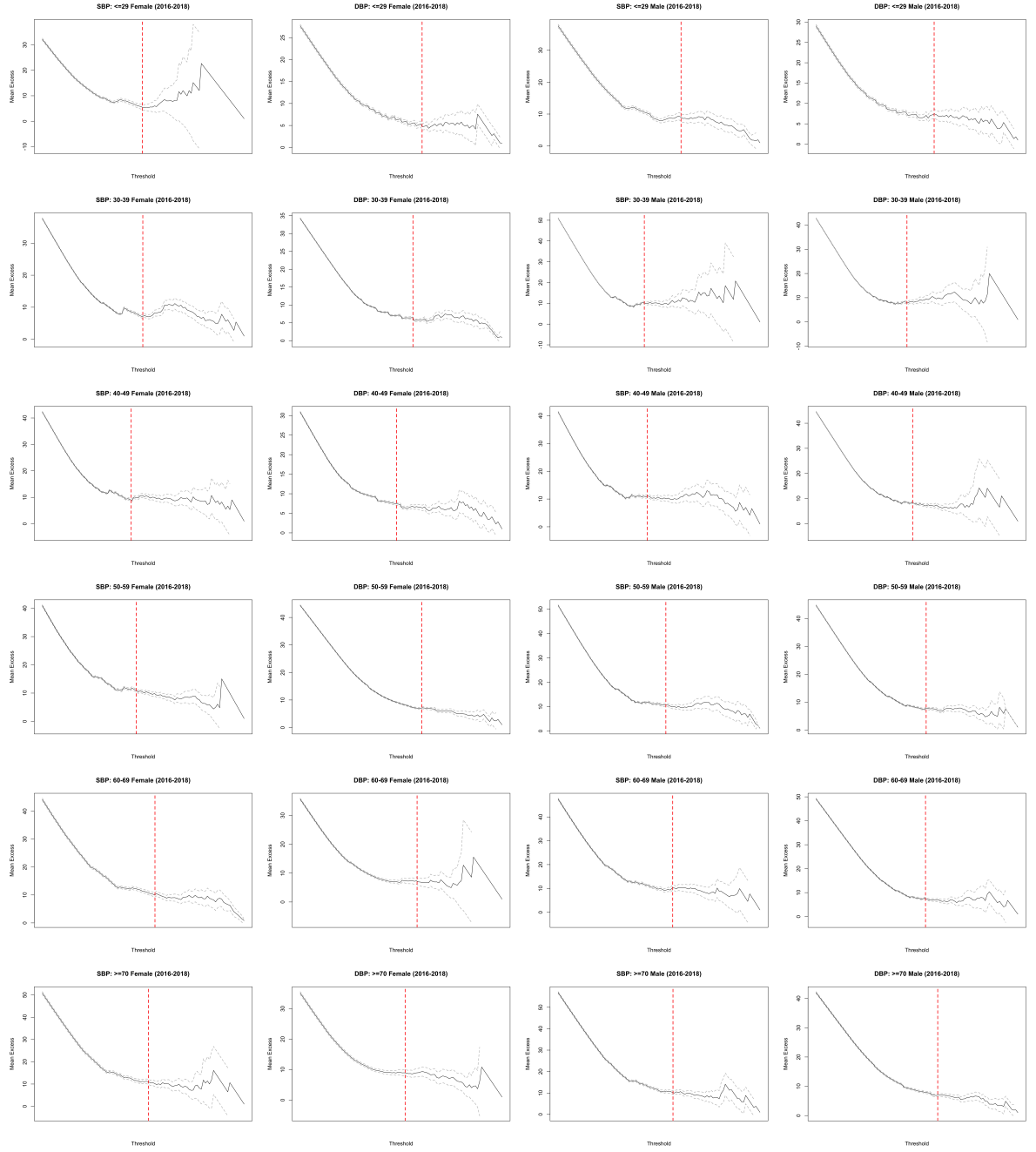


Fig. S12: Mean Residual Life plots (2011–2013)



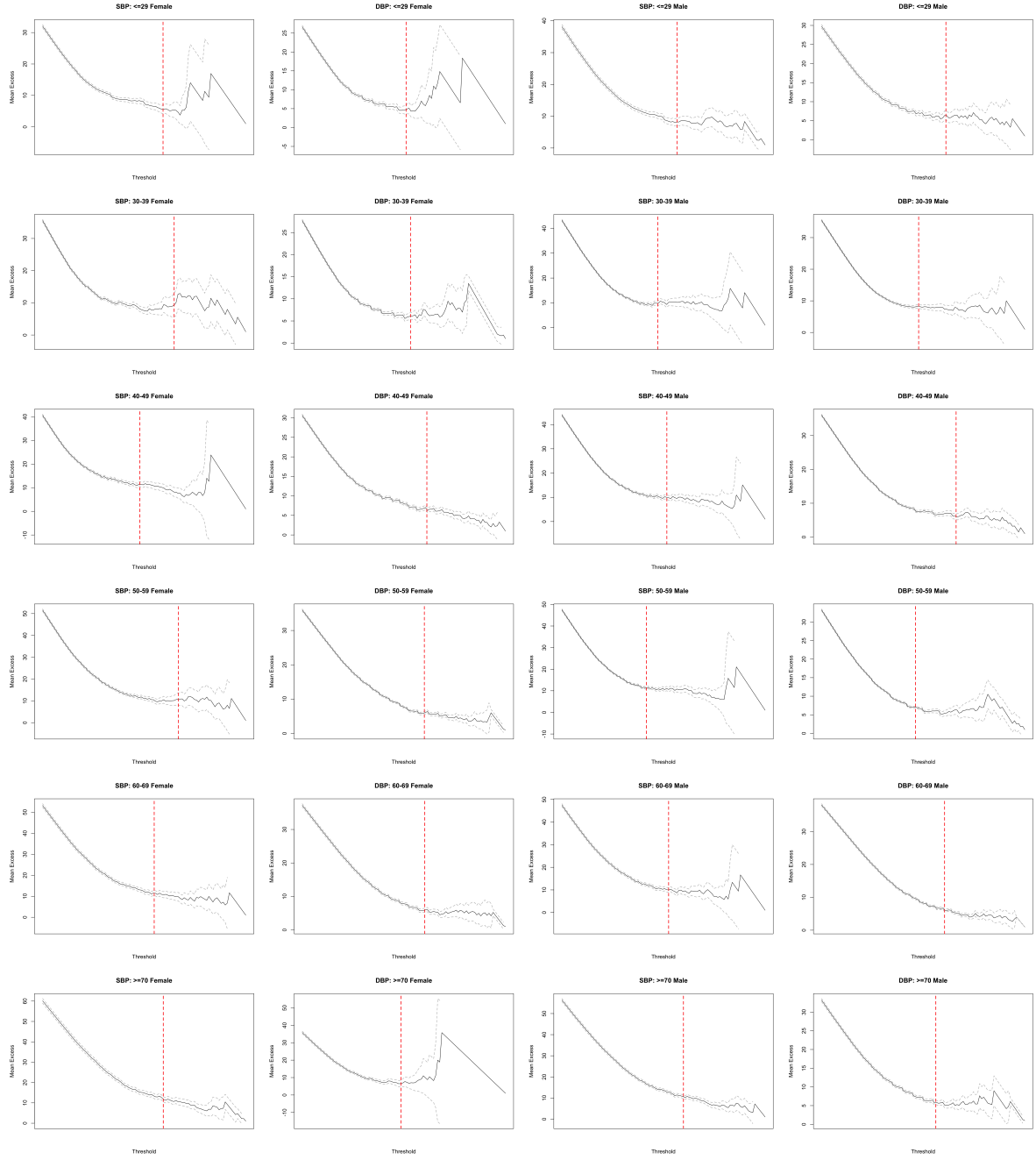
The red dashed line represents the selected threshold.

Fig. S13: Mean Residual Life plots (2016–2018)



The red dashed line represents the selected threshold.

Fig. S14: Mean Residual Life plots (2021–2023)



The red dashed line represents the selected threshold.

Appendix E Copula parameter estimation (2011–2013, 2016–2018)

Table S5: Mixed copula model analysis results (Age groups: ≤ 29 , 30–39, and 40–49, 2011–2013)

Age	Gender	Optimal Copula		Gumbel-Clayton		Gaussian-Gumbel		Gaussian-Clayton		Gaussian	Gumbel	Clayton
				Gumbel	Clayton	Gaussian	Gumbel	Gaussian	Clayton			
≤ 29	Female	Gaussian-Clayton	Weight (SE)	0.5260 (0.0156)	0.4740 (0.0148)	0.9388 (0.0209)	0.0612 (0.0053)	0.8011 (0.0193)	0.1989 (0.0096)	–	–	–
			Parameters (SE)	1.8143 (0.0809)	7.6100 (0.8242)	0.7528 (0.0163)	2.4710 (0.4007)	0.8235 (0.0137)	3.2793 (0.6130)	0.7603 (0.0154)	1.6951 (0.0510)	7.4725 (0.5688)
			AIC	–64.9033		–69.6213		–74.8184		–73.3928	–42.8522	–21.3855
			RMSE	0.0193		0.0193		0.0192		0.0193	0.0197	0.0206
	Male	Gaussian-Clayton	Weight (SE)	0.7913 (0.0183)	0.2087 (0.0094)	0.9647 (0.0202)	0.0353 (0.0039)	0.9274 (0.0198)	0.0726 (0.0056)	–	–	–
			Parameters (SE)	2.3212 (0.0571)	4.1151 (0.3826)	0.8477 (0.0065)	1.0604 (0.3015)	0.8574 (0.0063)	0.9265 (0.2399)	0.8149 (0.0076)	2.1874 (0.0469)	4.5077 (0.1909)
			AIC	388.7754		367.3486		361.7444		398.4601	408.0377	574.2271
			RMSE	0.0185		0.0179		0.0181		0.0187	0.0185	0.0262
30–39	Female	Gaussian-Clayton	Weight (SE)	0.7712 (0.0135)	0.2288 (0.0073)	0.4872 (0.0107)	0.5128 (0.0110)	0.8477 (0.0141)	0.1523 (0.0060)	–	–	–
			Parameters (SE)	2.0529 (0.0499)	5.3340 (0.5093)	0.8277 (0.0106)	1.8601 (0.0522)	0.8703 (0.0063)	1.7284 (0.2588)	0.7867 (0.0087)	1.9198 (0.0391)	6.4207 (0.2946)
			AIC	–34.3168		–30.9755		–41.7837		22.7059	–20.1040	214.4584
			RMSE	0.0146		0.0143		0.0142		0.0149	0.0147	0.0179
	Male	Gaussian-Gumbel	Weight (SE)	0.8054 (0.0119)	0.1946 (0.0059)	0.6827 (0.0110)	0.3173 (0.0075)	0.9724 (0.0131)	0.0276 (0.0022)	–	–	–
			Parameters (SE)	2.2965 (0.0329)	6.1786 (0.3150)	0.8532 (0.0044)	2.0872 (0.0467)	0.8179 (0.0044)	35.1220 (3.9545)	0.8217 (0.0043)	2.2759 (0.0292)	3.7751 (0.0932)
			AIC	1040.7041		984.4261		1074.6762		1073.4760	1083.8970	1821.1450
			RMSE	0.0176		0.0171		0.0176		0.0177	0.0186	0.0273
40–49	Female	Gaussian-Gumbel	Weight (SE)	0.9647 (0.0155)	0.0353 (0.0030)	0.4710 (0.0108)	0.5290 (0.0114)	0.9267 (0.0151)	0.0733 (0.0043)	–	–	–
			Parameters (SE)	2.3550 (0.0420)	16.8640 (2.6897)	0.8945 (0.0054)	2.2186 (0.0524)	0.8881 (0.0041)	1.1193 (0.2128)	0.8523 (0.0050)	2.3661 (0.0415)	5.6878 (0.1896)
			AIC	44.5334		21.5663		53.7065		82.7988	41.0681	574.4876
			RMSE	0.0152		0.0144		0.0143		0.0143	0.0154	0.0201
	Male	Gaussian-Clayton	Weight (SE)	0.7114 (0.0114)	0.2886 (0.0073)	0.9460 (0.0132)	0.0540 (0.0031)	0.9851 (0.0134)	0.0149 (0.0017)	–	–	–
			Parameters (SE)	2.4444 (0.0366)	5.2566 (0.2067)	0.8603 (0.0034)	1.3899 (0.0651)	0.8541 (0.0035)	–0.4178 (0.0000)	0.8317 (0.0039)	2.3787 (0.0299)	3.6504 (0.0838)
			AIC	1098.2262		1006.2710		1005.2707		1138.7290	1211.4390	1899.6730
			RMSE	0.0165		0.0158		0.0159		0.0173	0.0180	0.0293

1. Standard errors are reported in parentheses.
2. The optimal copula for each group is selected based on the minimum AIC.

Table S6: Mixed copula model analysis results (Age groups: 50–59, 60–69, and ≥ 70 , 2011–2013)

Age	Gender	Optimal Copula	Gumbel–Clayton		Gaussian–Gumbel		Gaussian–Clayton		Gaussian	Gumbel	Clayton	
			Gumbel	Clayton	Gaussian	Gumbel	Gaussian	Clayton				
50–59	Female	Gaussian–Gumbel	Weight	0.5573	0.4427	0.9830	0.0170	0.8255	0.1745	–	–	–
			(SE)	(0.0119)	(0.0106)	(0.0158)	(0.0021)	(0.0145)	(0.0067)	–	–	–
			Parameters	2.3424	6.5637	0.8496	1.2032	0.8245	10.4724	0.8356	2.3004	4.4651
			(SE)	(0.0481)	(0.2587)	(0.0044)	(0.1082)	(0.0055)	(0.6224)	(0.0048)	(0.0351)	(0.1260)
			AIC	674.6537		626.4074		660.2972		671.9788	838.4277	1027.021
	Male	Gaussian–Clayton	RMSE	0.0129		0.0124		0.0126		0.0129	0.0147	0.0207
			Weight	0.6757	0.3243	0.9839	0.0161	0.9898	0.0102	–	–	–
			(SE)	(0.0119)	(0.0082)	(0.0143)	(0.0018)	(0.0144)	(0.0015)	–	–	–
			Parameters	2.3329	4.8199	0.8330	1.0010	0.8309	–0.3290	0.8144	2.2912	3.1801
			(SE)	(0.0369)	(0.1835)	(0.0040)	(0.0000)	(0.0041)	(0.1005)	(0.0044)	(0.0297)	(0.0760)
60–69	Female	Gaussian–Clayton	AIC	1083.8521		1008.6821		1007.5671		1113.254	1211.249	1737.391
			RMSE	0.0147		0.0145		0.0144		0.0155	0.0167	0.0276
			Weight	0.4477	0.5523	0.9649	0.0351	0.6563	0.3437	–	–	–
			(SE)	(0.0159)	(0.0177)	(0.0234)	(0.0045)	(0.0193)	(0.0140)	–	–	–
			Parameters	2.0619	4.1928	0.8045	1.0275	0.7474	5.4755	0.7736	2.0421	2.8845
	Male	Gaussian–Clayton	(SE)	(0.0639)	(0.2032)	(0.0077)	(0.1082)	(0.0117)	(0.3190)	(0.0086)	(0.0423)	(0.1146)
			AIC	612.9991		626.8499		612.0696		643.1270	769.1650	729.5236
			RMSE	0.0157		0.0158		0.0154		0.0168	0.0203	0.0252
			Weight	0.5901	0.4099	0.9919	0.0081	0.9850	0.0150	–	–	–
			(SE)	(0.0143)	(0.0119)	(0.0185)	(0.0017)	(0.0184)	(0.0023)	–	–	–
≥ 70	Female	Gumbel–Clayton	Parameters	2.1653	3.1210	0.7840	1.0010	0.7861	0.3402	0.7753	2.0839	2.3943
			(SE)	(0.0448)	(0.1382)	(0.0062)	(0.1082)	(0.0062)	(0.2529)	(0.0064)	(0.0331)	(0.0734)
			AIC	938.3537		883.6706		883.5213		901.8131	1049.357	1245.346
			RMSE	0.0191		0.0176		0.0176		0.0180	0.0211	0.0312
			Weight	0.4503	0.5497	0.7364	0.2636	0.5701	0.4299	–	–	–
	Male	Gumbel–Clayton	(SE)	(0.0251)	(0.0277)	(0.0321)	(0.0192)	(0.0282)	(0.0245)	–	–	–
			Parameters	1.7899	3.0291	0.6223	3.9830	0.6123	4.0385	0.6971	1.8507	1.8590
			(SE)	(0.0831)	(0.2215)	(0.0235)	(0.2645)	(0.0274)	(0.3091)	(0.0167)	(0.0583)	(0.1215)
			AIC	253.0789		264.7041		265.4473		280.0329	308.1010	321.2173
			RMSE	0.0206		0.0219		0.0217		0.0239	0.0275	0.0324
Male	Gumbel–Clayton	Weight	0.5296	0.4704	0.7438	0.2562	0.7216	0.2784	–	–	–	
		(SE)	(0.0174)	(0.0164)	(0.0206)	(0.0121)	(0.0203)	(0.0126)	–	–	–	
		Parameters	1.8745	2.4688	0.6253	2.9318	0.6490	3.5703	0.6837	1.8099	1.6674	
		(SE)	(0.0513)	(0.1338)	(0.0149)	(0.1219)	(0.0143)	(0.2256)	(0.0111)	(0.0359)	(0.0721)	
		AIC	683.5276		712.8924		711.7025		729.1368	795.2784	857.4110	
RMSE	0.0171		0.0179		0.0179		0.0190	0.0221	0.0306			

1. Standard errors are reported in parentheses.
2. The optimal copula for each subgroup is selected based on the minimum AIC.

Table S7: Mixed copula model analysis results (Age groups: ≤ 29 , 30–39, and 40–49, 2016–2018)

Age	Gender	Optimal Copula	Gumbel–Clayton		Gaussian–Gumbel		Gaussian–Clayton		Gaussian	Gumbel	Clayton
			Gumbel	Clayton	Gaussian	Gumbel	Gaussian	Clayton			
≤ 29	Female	Gaussian–Clayton	Weight	0.6486	0.3514	0.6286	0.3714	0.9118	0.0882	–	–
			(SE)	(0.0136)	(0.0100)	(0.0134)	(0.0103)	(0.0161)	(0.0050)	–	–
			Parameters	1.9892	7.4502	0.7931	1.9519	0.8362	1.5620	0.7887	1.8730
			(SE)	(0.0593)	(0.6313)	(0.0122)	(0.0762)	(0.0085)	(0.3679)	(0.0099)	(0.0427)
			(0.3534)								
	Male	Gaussian–Gumbel	AIC	3.2758		3.3757		1.6833		17.2430	33.4536
			RMSE	0.0198		0.0243		0.0178		0.0209	0.0356
			Weight	0.8704	0.1296	0.4710	0.5290	0.9468	0.0532	–	–
			(SE)	(0.0160)	(0.0062)	(0.0118)	(0.0125)	(0.0167)	(0.0040)	–	–
			Parameters	2.1972	6.8394	0.8429	2.1292	0.8000	60.9306	0.8079	2.1873
30–39	Female	Gaussian–Gumbel	(SE)	(0.0409)	(0.6035)	(0.0078)	(0.0506)	(0.0067)	(7.3430)	(0.0063)	(0.0380)
			AIC	613.8521		599.7782		669.6292		672.9501	622.2723
			RMSE	0.0229		0.0218		0.0197		0.0202	0.0267
			Weight	0.9315	0.0685	0.4343	0.5657	0.9421	0.0579	–	–
			(SE)	(0.0081)	(0.0022)	(0.0055)	(0.0063)	(0.0082)	(0.0020)	–	–
	Male	Gaussian–Gumbel	Parameters	2.0793	8.2124	0.8631	1.9940	0.8674	0.5956	0.8181	2.0634
			(SE)	(0.0248)	(0.7344)	(0.0050)	(0.0300)	(0.0033)	(0.1298)	(0.0041)	(0.0236)
			AIC	–606.9541		–642.2958		–585.5334		–384.1408	–612.6067
			RMSE	0.0265		0.0222		0.0149		0.0174	0.0295
			Weight	0.9508	0.0492	0.3585	0.6415	0.9446	0.0554	–	–
40–49	Female	Gaussian–Gumbel	(SE)	(0.0076)	(0.0017)	(0.0046)	(0.0062)	(0.0075)	(0.0018)	–	–
			Parameters	2.3588	6.0932	0.8612	2.3088	0.8658	0.3734	0.8275	2.3492
			(SE)	(0.0186)	(0.3724)	(0.0034)	(0.0220)	(0.0020)	(0.0690)	(0.0025)	(0.0180)
			AIC	2451.4310		2386.9683		2605.0860		2915.1373	2457.2526
			RMSE	0.0240		0.0218		0.0178		0.0190	0.0254
	Male	Gaussian–Gumbel	Weight	0.8689	0.1311	0.5574	0.4426	0.9578	0.0422	–	–
			(SE)	(0.0081)	(0.0031)	(0.0065)	(0.0058)	(0.0085)	(0.0018)	–	–
			Parameters	2.4617	8.2788	0.8915	2.2817	0.8925	0.8314	0.8620	2.4016
			(SE)	(0.0273)	(0.4240)	(0.0030)	(0.0345)	(0.0022)	(0.1397)	(0.0027)	(0.0245)
			AIC	–640.4935		–705.0047		–680.7806		–457.8745	–610.5493
40–49	Female	Gaussian–Gumbel	RMSE	0.0245		0.0221		0.0175		0.0194	0.0295
			Weight	0.9682	0.0318	0.3552	0.6448	0.9390	0.0610	–	–
			(SE)	(0.0079)	(0.0014)	(0.0048)	(0.0064)	(0.0077)	(0.0020)	–	–
			Parameters	2.6917	11.6311	0.8925	2.6663	0.8610	36.3995	0.8676	2.6947
			(SE)	(0.0209)	(0.7608)	(0.0026)	(0.0254)	(0.0020)	(1.5177)	(0.0019)	(0.0206)
	Male	Gaussian–Gumbel	AIC	–53.1158		–140.3091		440.3600		476.5309	–46.7868
			RMSE	0.0180		0.0162		0.0136		0.0136	0.0185
			Weight	0.9682	0.0318	0.3552	0.6448	0.9390	0.0610	–	–
			(SE)	(0.0079)	(0.0014)	(0.0048)	(0.0064)	(0.0077)	(0.0020)	–	–
			Parameters	2.6917	11.6311	0.8925	2.6663	0.8610	36.3995	0.8676	2.6947
40–49	Female	Gaussian–Gumbel	(SE)	(0.0209)	(0.7608)	(0.0026)	(0.0254)	(0.0020)	(1.5177)	(0.0019)	(0.0206)
			AIC	–53.1158		–140.3091		440.3600		476.5309	–46.7868
			RMSE	0.0180		0.0162		0.0136		0.0136	0.0185
			Weight	0.9682	0.0318	0.3552	0.6448	0.9390	0.0610	–	–
			(SE)	(0.0079)	(0.0014)	(0.0048)	(0.0064)	(0.0077)	(0.0020)	–	–
	Male	Gaussian–Gumbel	Parameters	2.6917	11.6311	0.8925	2.6663	0.8610	36.3995	0.8676	2.6947
			(SE)	(0.0209)	(0.7608)	(0.0026)	(0.0254)	(0.0020)	(1.5177)	(0.0019)	(0.0206)
			AIC	–53.1158		–140.3091		440.3600		476.5309	–46.7868
			RMSE	0.0180		0.0162		0.0136		0.0136	0.0185
			Weight	0.9682	0.0318	0.3552	0.6448	0.9390	0.0610	–	–

1. Standard errors are reported in parentheses.

2. The optimal copula for each subgroup is selected based on the minimum AIC among all six candidate models.

Table S8: Mixed copula model analysis results (Age groups: 50–59, 60–69, and ≥ 70 , 2016–2018)

Age	Gender	Optimal Copula		Gumbel–Clayton		Gaussian–Gumbel		Gaussian–Clayton		Gaussian	Gumbel	Clayton
				Gumbel	Clayton	Gaussian	Gumbel	Gaussian	Clayton			
50–59	Female	Gaussian–Gumbel	Weight	0.6178	0.3822	0.9631	0.0369	0.8576	0.1424	–	–	–
			(SE)	(0.0073)	(0.0058)	(0.0092)	(0.0018)	(0.0087)	(0.0035)	–	–	–
			Parameters	2.4285	7.1402	0.8702	1.2724	0.8408	10.6881	0.8475	2.3837	4.7796
			(SE)	(0.0278)	(0.1749)	(0.0023)	(0.0467)	(0.0029)	(0.4120)	(0.0026)	(0.0214)	(0.0775)
			AIC	1431.8223		1256.3354		1376.8992		1412.2343	1815.9086	2594.6963
			RMSE	0.0146		0.0147		0.0137		0.0156	0.0258	0.0154
	Male	Gaussian–Gumbel	Weight	0.7669	0.2331	0.7788	0.2212	0.9712	0.0288	–	–	–
			(SE)	(0.0076)	(0.0042)	(0.0076)	(0.0041)	(0.0085)	(0.0015)	–	–	–
			Parameters	2.7931	6.1102	0.8889	2.4334	0.8869	0.6878	0.8718	2.7088	4.2335
			(SE)	(0.0253)	(0.1550)	(0.0018)	(0.0404)	(0.0017)	(0.1069)	(0.0019)	(0.0214)	(0.0558)
			AIC	434.8236		221.8816		239.0617		383.4729	684.7960	2817.2712
			RMSE	0.0136		0.0127		0.0119		0.0124	0.0187	0.0202
60–69	Female	Gaussian–Clayton	Weight	0.6261	0.3739	0.9296	0.0704	0.9091	0.0909	–	–	–
			(SE)	(0.0109)	(0.0085)	(0.0133)	(0.0037)	(0.0132)	(0.0042)	–	–	–
			Parameters	2.2001	5.6022	0.8501	1.1735	0.8558	0.6252	0.8039	2.2407	3.1330
			(SE)	(0.0342)	(0.1835)	(0.0036)	(0.0441)	(0.0035)	(0.0964)	(0.0044)	(0.0277)	(0.0725)
			AIC	1266.6966		1211.2467		1198.9088		1350.2526	1465.3715	1925.3988
			RMSE	0.0129		0.0126		0.0123		0.0141	0.0202	0.0209
	Male	Gaussian–Clayton	Weight	0.6356	0.3644	0.9686	0.0314	0.9680	0.0320	–	–	–
			(SE)	(0.0091)	(0.0069)	(0.0112)	(0.0020)	(0.0112)	(0.0020)	–	–	–
			Parameters	2.4594	4.4290	0.8478	1.2404	0.8487	0.4843	0.8293	2.3714	3.1567
			(SE)	(0.0305)	(0.1183)	(0.0028)	(0.0582)	(0.0028)	(0.1117)	(0.0031)	(0.0234)	(0.0551)
			AIC	1364.7565		1208.9062		1205.0410		1290.3056	1677.8134	2442.5514
			RMSE	0.0144		0.0139		0.0138		0.0146	0.0217	0.0227
≥ 70	Female	Gaussian–Gumbel	Weight	0.5710	0.4290	0.8934	0.1066	0.7123	0.2877	–	–	–
			(SE)	(0.0131)	(0.0113)	(0.0164)	(0.0056)	(0.0146)	(0.0093)	–	–	–
			Parameters	1.7660	3.3227	0.7880	1.0010	0.6343	4.9512	0.6926	1.8400	1.8353
			(SE)	(0.0328)	(0.1290)	(0.0059)	(0.0000)	(0.0108)	(0.2116)	(0.0078)	(0.0263)	(0.0578)
			AIC	977.9668		928.4369		1056.9315		1092.1711	1108.6552	1401.3786
			RMSE	0.0180		0.0190		0.0171		0.0187	0.0247	0.0160
	Male	Gaussian–Gumbel	Weight	0.5288	0.4712	0.9104	0.0896	0.6778	0.3222	–	–	–
			(SE)	(0.0092)	(0.0086)	(0.0120)	(0.0038)	(0.0104)	(0.0071)	–	–	–
			Parameters	2.0519	3.0834	0.8190	1.0010	0.7169	3.6502	0.7381	1.9976	2.1287
			(SE)	(0.0299)	(0.0813)	(0.0036)	(0.0000)	(0.0064)	(0.1110)	(0.0049)	(0.0213)	(0.0442)
			AIC	1527.9754		1432.3949		1665.0885		1774.3628	1946.2848	2267.0155
			RMSE	0.0154		0.0152		0.0162		0.0177	0.0222	0.0260

1. Standard errors are reported in parentheses.

2. The optimal copula for each subgroup is selected based on the minimum AIC among all six candidate models.

Appendix F Results of Breusch–Pagan test

Table S9: Results of Breusch–Pagan test across age–sex subgroups and study periods

Age Group	2011–2013		2016–2018		2021–2023	
	Female	Male	Female	Male	Female	Male
≤ 29	10.91***	1.16	7.60**	8.78**	9.15**	17.24***
30–39	6.48*	7.53*	12.72***	26.45***	9.02**	4.29
40–49	8.77**	8.42**	13.88***	10.04**	13.31***	10.89**
50–59	15.01***	1.11	4.01	4.46	2.77	12.54***
60–69	1.73	9.69**	7.88**	13.14***	18.90***	14.66***
≥ 70	11.29**	10.11**	27.52***	36.09***	4.69	8.63**

1. Reported values are test statistics from the Breusch–Pagan test.

2. * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Appendix G WLS regression results (2011–2013, 2016–2018)

Table S10: Age-adjusted WLS estimates for the association between BMI and BP index across age-sex subgroups (2011–2013)

Age group	Female				Male			
	β_0	β_{BMI}	β_{Age}	β_{Diabetes}	β_0	β_{BMI}	β_{Age}	β_{Diabetes}
≤ 29	0.7416*** (0.0867)	0.0060*** (0.0019)	−0.0008 (0.0030)	— —	0.2778*** (0.0737)	0.0103*** (0.0014)	0.0071*** (0.0025)	— —
30–39	0.5767*** (0.0725)	0.0096*** (0.0012)	0.0008 (0.0018)	−0.0078 (0.0395)	0.1623*** (0.0542)	0.0149*** (0.0011)	0.0032** (0.0013)	0.0617** (0.0261)
40–49	0.2987*** (0.0773)	0.0106*** (0.0012)	0.0044*** (0.0016)	0.0531*** (0.0203)	0.0123 (0.0629)	0.0167*** (0.0011)	0.0038*** (0.0012)	0.0265 (0.0164)
50–59	0.1798** (0.0816)	0.0111*** (0.0013)	0.0039*** (0.0014)	0.0552*** (0.0193)	0.0540 (0.0793)	0.0178*** (0.0014)	0.0012 (0.0013)	0.0741*** (0.0151)
60–69	0.2062 (0.1505)	0.0101*** (0.0021)	0.0017 (0.0022)	−0.0038 (0.0255)	0.1226 (0.1180)	0.0112*** (0.0018)	0.0016 (0.0017)	0.0629*** (0.0177)
≥ 70	0.1663 (0.1516)	0.0092*** (0.0029)	0.0009 (0.0017)	0.0920** (0.0454)	0.1714* (0.0962)	0.0102*** (0.0022)	0.0004 (0.0009)	0.0696*** (0.0213)

1. Standard errors are reported in parentheses.
2. ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
3. — indicates that the coefficient was not estimated.

Table S11: Age-adjusted WLS estimates for the association between BMI and BP index across age-sex subgroups (2016–2018)

Age group	Female				Male			
	β_0	β_{BMI}	β_{Age}	β_{Diabetes}	β_0	β_{BMI}	β_{Age}	β_{Diabetes}
≤ 29	0.5695*** (0.0572)	0.0084*** (0.0009)	0.0028 (0.0019)	— —	0.2680*** (0.0563)	0.0118*** (0.0012)	0.0050*** (0.0018)	— —
30–39	0.5628*** (0.0413)	0.0085*** (0.0007)	0.0020* (0.0011)	0.0676*** (0.0183)	0.1624*** (0.0322)	0.0153*** (0.0006)	0.0034*** (0.0008)	0.0462*** (0.0157)
40–49	0.3946*** (0.0406)	0.0089*** (0.0007)	0.0040*** (0.0008)	0.0320** (0.0133)	0.0850** (0.0382)	0.0165*** (0.0007)	0.0029*** (0.0007)	0.0594*** (0.0101)
50–59	0.2259*** (0.0542)	0.0118*** (0.0008)	0.0029*** (0.0009)	0.0288** (0.0117)	0.0458 (0.0486)	0.0171*** (0.0008)	0.0022*** (0.0008)	0.0279*** (0.0081)
60–69	0.2168** (0.0858)	0.0147*** (0.0012)	−0.0001 (0.0013)	0.0558*** (0.0149)	0.2429*** (0.0730)	0.0121*** (0.0011)	0.0001 (0.0010)	0.0342*** (0.0095)
≥ 70	0.1276* (0.0770)	0.0086*** (0.0016)	0.0021** (0.0008)	0.0191 (0.0176)	0.2954*** (0.0568)	0.0100*** (0.0012)	−0.0006 (0.0006)	0.0377*** (0.0102)

1. Standard errors are reported in parentheses.
2. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
3. — indicates that the coefficient was not estimated.

Appendix H Pairwise contrasts of BMI coefficients

Table S12: Pairwise contrasts of BMI coefficients across study periods

Age group	Sex	2016–2018 vs. 2011–2013	2021–2023 vs. 2011–2013	2021–2023 vs. 2016–2018
≤ 29	Female	0.0021 (0.0022)	0.0004 (0.0025)	−0.0018 (0.0017)
	Male	0.0019 (0.0018)	−0.0007 (0.0022)	−0.0026 (0.0021)
30–39	Female	−0.0008 (0.0014)	−0.0029 (0.0019)	−0.0021 (0.0016)
	Male	0.0004 (0.0012)	−0.0027 (0.0016)	−0.0031* (0.0013)
40–49	Female	−0.0019 (0.0014)	0.0012 (0.0018)	0.0031* (0.0014)
	Male	0.0000 (0.0013)	−0.0048*** (0.0016)	−0.0048*** (0.0014)
50–59	Female	0.0005 (0.0015)	−0.0015 (0.0018)	−0.0020 (0.0016)
	Male	−0.0011 (0.0016)	−0.0068*** (0.0018)	−0.0056*** (0.0014)
60–69	Female	0.0051* (0.0023)	−0.0002 (0.0028)	−0.0053* (0.0023)
	Male	0.0009 (0.0021)	0.0023 (0.0026)	0.0014 (0.0022)
≥ 70	Female	−0.0014 (0.0033)	−0.0014 (0.0036)	−0.0001 (0.0027)
	Male	−0.0001 (0.0024)	−0.0075** (0.0027)	−0.0073*** (0.0022)

1. Reported values are pairwise differences in BMI coefficients between the indicated study periods.
2. Positive values indicate that the BMI coefficient was larger in the later period.
3. Pairwise P values were adjusted using the Holm method within each age–sex subgroup.
4. ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Appendix I Sensitivity analysis about initial location parameter

Table S13: Parameter estimates under the 95% initial setting

Age	Sex	Measure	(μ_1, σ_1)		(μ_2, σ_2, ξ)			Log-likelihood
			μ_1	σ_1	μ_2	σ_2	ξ	
≤ 29	Female	SBP	4.6571	0.0941	143.7463	4.5709	0.3209	-7143.757
		DBP	4.2209	0.1200	91.3590	2.3658	0.5170	-6601.492
	Male	SBP	4.7783	0.1109	139.9309	8.7286	-0.0353	-6856.795
		DBP	4.3031	0.1292	90.9953	6.1029	-0.0235	-6293.389
30-39	Female	SBP	4.6671	0.1114	135.3878	8.0078	0.0829	-16826.213
		DBP	4.2279	0.1209	88.3718	6.9000	0.0392	-15456.101
	Male	SBP	4.7959	0.1074	136.4937	8.8446	0.0449	-20979.697
		DBP	4.3485	0.1294	88.4694	7.6282	-0.0175	-19630.829
40-49	Female	SBP	4.7458	0.1353	138.3802	11.8064	-0.0485	-18869.946
		DBP	4.2768	0.1395	90.2909	8.4729	-0.2086	-17116.368
	Male	SBP	4.8168	0.1149	145.8237	10.2047	-0.0341	-23231.456
		DBP	4.3977	0.1332	97.3771	6.9405	-0.0479	-21540.860
50-59	Female	SBP	4.8302	0.1411	144.9888	9.0040	0.0247	-18156.311
		DBP	4.3799	0.1648	89.8093	6.3566	-0.1067	-16085.789
	Male	SBP	4.8453	0.1360	139.5744	11.9005	-0.0478	-28756.643
		DBP	4.4137	0.1505	91.6951	7.8457	-0.0724	-25880.610
60-69	Female	SBP	4.9041	0.1368	153.3945	10.5599	-0.0944	-8099.701
		DBP	4.3936	0.1499	87.1196	6.9150	-0.1181	-7003.999
	Male	SBP	4.8928	0.1262	157.4025	9.1655	-0.0708	-11543.505
		DBP	4.4028	0.1419	91.8609	7.7979	-0.1838	-10089.763
70-79	Female	SBP	4.9831	0.1287	172.2274	12.1672	-0.9961	-4468.631
		DBP	4.3920	0.1537	88.1079	6.0422	0.0700	-3986.176
	Male	SBP	4.9747	0.1425	166.3797	11.3900	-0.1891	-10614.712
		DBP	4.3921	0.1505	89.2072	6.4326	-0.0724	-10063.259

Table S14: Parameter estimates under the 85% initial setting

Age	Sex	Measure	(μ_1, σ_1)		(μ_2, σ_2, ξ)			Log-likelihood
			μ_1	σ_1	μ_2	σ_2	ξ	
≤ 29	Female	SBP	4.6584	0.0948	144.3842	4.6268	0.3390	-7144.184
		DBP	4.2209	0.1200	86.3408	3.2871	0.5126	-6601.492
	Male	SBP	4.7788	0.1113	138.3598	8.7639	-0.0303	-6856.689
		DBP	4.3028	0.1289	88.9051	6.4175	-0.0344	-6293.352
30-39	Female	SBP	4.6671	0.1014	141.2559	9.1020	0.0829	-16826.213
		DBP	4.2311	0.1231	92.3933	6.3384	0.0183	-15456.928
	Male	SBP	4.7959	0.1074	138.0547	8.7773	0.0450	-20979.697
		DBP	4.3485	0.1294	89.0087	7.6189	-0.0175	-19630.829
40-49	Female	SBP	4.7401	0.1288	140.5570	11.4117	-0.0534	-18861.424
		DBP	4.2882	0.1487	91.6938	7.8392	-0.2343	-17115.895
	Male	SBP	4.8168	0.1149	131.7776	10.6769	-0.0337	-23231.456
		DBP	4.3977	0.1332	89.4651	7.3043	-0.0469	-21540.860
50-59	Female	SBP	4.8302	0.1411	145.0950	8.7460	0.0249	-18156.311
		DBP	4.3698	0.1554	90.4420	6.3141	-0.0913	-16083.835
	Male	SBP	4.8453	0.1360	144.9846	11.9351	-0.0478	-28756.643
		DBP	4.4207	0.1467	90.9786	6.0593	-0.0907	-25882.024
60-69	Female	SBP	4.9042	0.1368	155.3108	9.7905	-0.1046	-8099.694
		DBP	4.3726	0.1393	91.6163	7.1812	-0.1234	-7003.963
	Male	SBP	4.8926	0.1261	160.4015	9.5356	-0.0444	-11543.487
		DBP	4.4027	0.1514	92.0000	7.0283	-0.2011	-10088.537
70-79	Female	SBP	4.9836	0.1280	171.4820	12.3900	-1.0593	-4468.508
		DBP	4.3781	0.1683	86.6626	7.8198	0.0466	-3984.006
	Male	SBP	4.9709	0.1368	159.0915	11.4044	-0.1668	-10618.060
		DBP	4.3969	0.1523	91.2999	6.3741	-0.0724	-10062.928