Supplementary material

Evaluation of the Environmental Performance of Cropping Systems under Different Nitrogen Management Scenarios Considering Regional Nitrogen Resilience

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Supplementary File S2

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1 Sensitivity and uncertainty analysis

1.1 *Regional normalization references and background interventions*

The distribution of rNR_{BI} values assessed along all German NUTS-3 regions is displayed in Figure S1 for both impact categories and LCIA methods IMPACT WORLD+ (for TAP regional and national level) an EF method (TAP and TEP national). The results show the confidence interval (95%), mean and standard deviation. The case study examples showed that current background interventions are higher in some regions than the set regional normalization references. However, the uncertainty analysis revealed that for most regions, rNR and BI values are similar, meaning rNR_{BI} is in most cases positive and nearly evenly distributed around zero. Uncertainty was given with 30% dispersion of values around the mean for TAP impacts. The highest uncertainty was observed for the TEP category, with a variation coefficient of more than 50%. Overall, the analysis confirmed that the current background interventions of non-crop producing sectors in most regions are lower than the regional normalization references set.

1.2 *Sensitivity on the choice of LCIA method*

The environmental interventions for all regions and scenarios were also calculated by applying national CF for LCIA methods IMPACT World+ and EF method for TAP. The results are presented in Figure S2 and **Figure** S3. Overall, the impacts are higher for the environmental intervention when assessed with the EF method (national) than with regional CF (+7% for Mecklenburgische Seenplatte and up to +46% for Kassel). Differences between IMPACT World+ national and regional CF are -3% for Mecklenburgische Seenplatte and highest for Kassel with − 31% when IMPACT World+ national is used for assessing the N-catch crop scenario. For the region Emsland, the main differences were observed for the N-catch crop scenario. Within this scenario, sensitivities result in a 20% lower EI for the N-catch crop scenario when applied with national CF. Generally, both LCIA methods consider the same driving flows for acidifying impacts. Therefore, the main differences are observed only when applying different spatial levels.

1.3 *Uncertainty of LCI data*

The results of the Monte Carlo analysis are presented for all regions and all scenarios in Table S1 and Figures SM4 - SM18. Analysis was done with IMPACT World+ method for TAP (regional) and the EF method for TAP (national) and TEP. The results show the confidence interval (95%), mean and standard deviation. The analysis is based on the variation of the input parameter Nmin. High uncertainties are observed for Ansbach and Emsland, especially for the scenarios N-catch crop and N-management. For both regions and scenarios, the variation coefficient (>100%) showed high dispersions around the mean, which are mainly caused due to outliers in the data. Here the parameter Nmin showed the highest sensitivity. High uncertainty was also observed for both, N-catch crop and N-management scenarios for Kassel; however, only when calculated with IMPACT world+ regional. Mecklenburgische Seenplatte and Spree-Neiße showed the lowest uncertainty with variation coefficients of less than 10 %.

For comparison of the different scenarios, 95% probability ranges based on the confidence intervals (CI) were taken into account. Differences in impact scores within one observed region between the N-base and N-catch crop and N-organic scenarios were deemed statistically significant for all regions (i.e. the calculated 95% probability ranges

of the impact scores did not overlap). For the regions Kassel and Spree-Neiße also, differences between N-base and N-management were observed as significant, whereas for the other regions not. Differences between regions, e.g. N-base Ansbach and N-base Spree-Neiße were deemed significant for all scenarios.

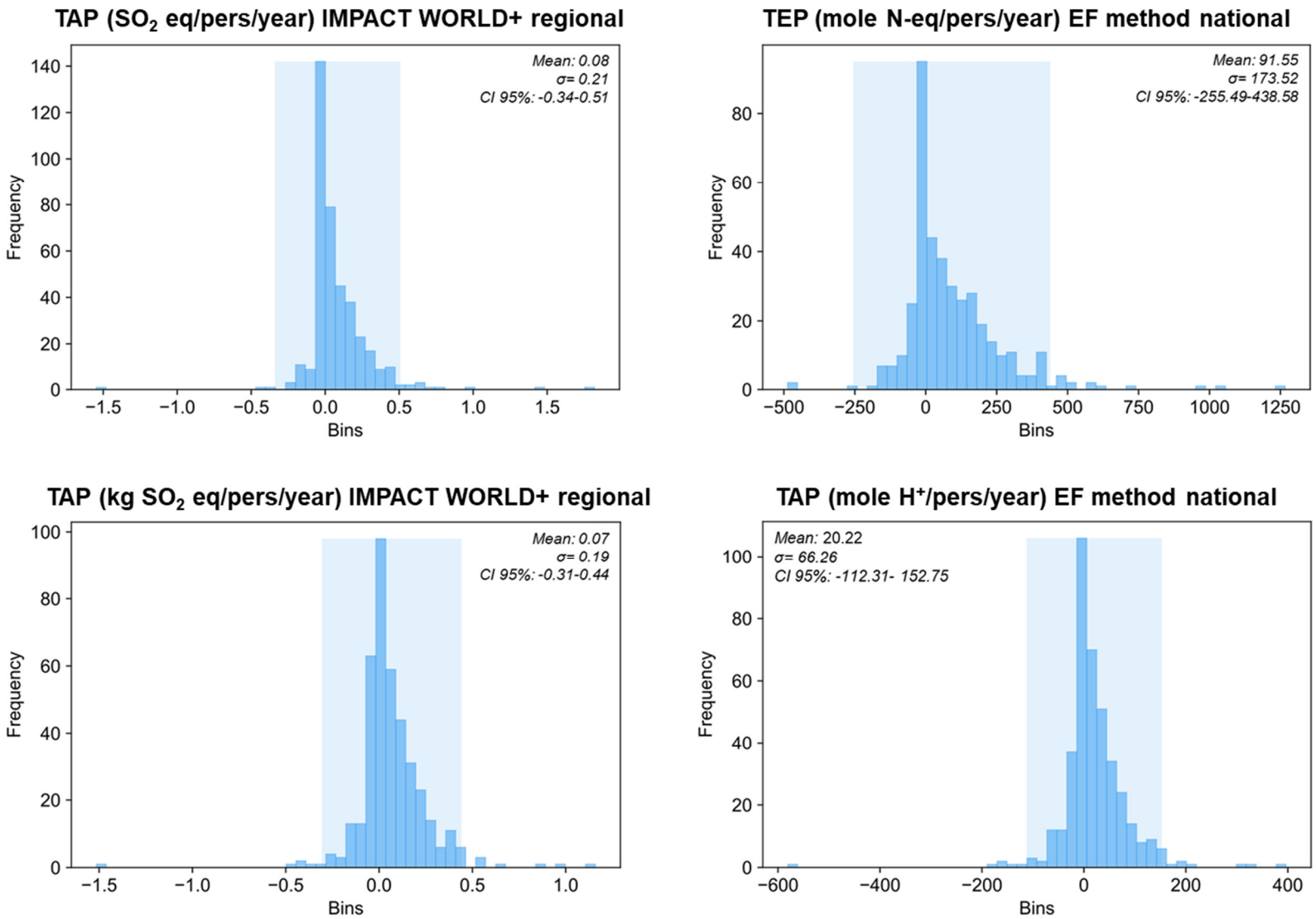

Figure S1. Distribution of regional normalization reference considering background intervention rNRBI for all LCIA methods considered. Figure shows mean, CI = Confidence interval and standard deviation. (TAP= Terrestrial acidification potential TEP = Terrestrial eutrophication potential)

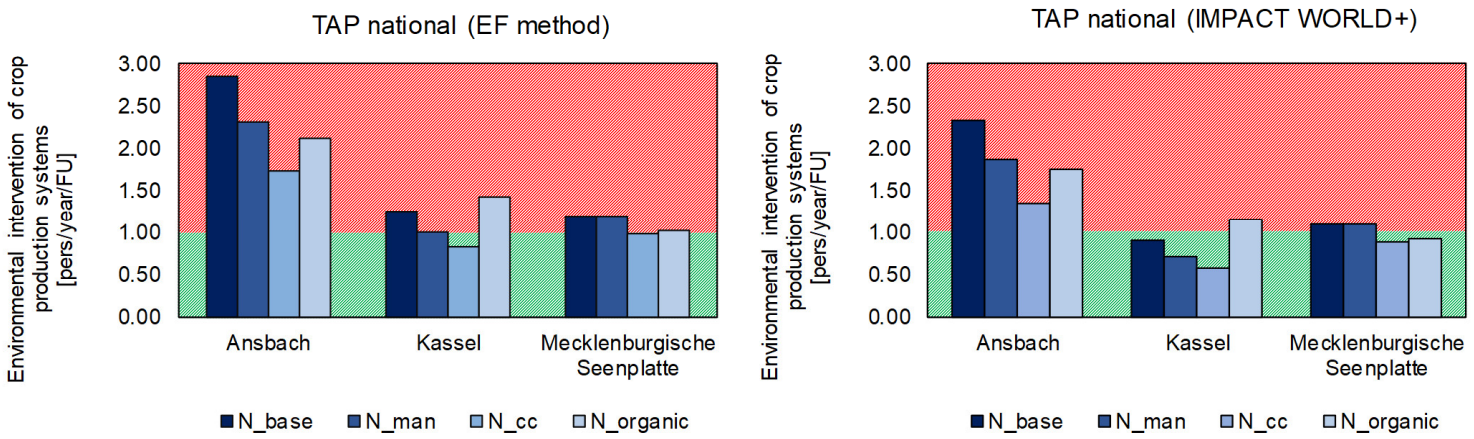

Figure S2. Environmental intervention calculated with nation CF for terrestrial acidification impacts (TAP). (EF = Environmental Footprint, CF = Characterization factor, Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario)

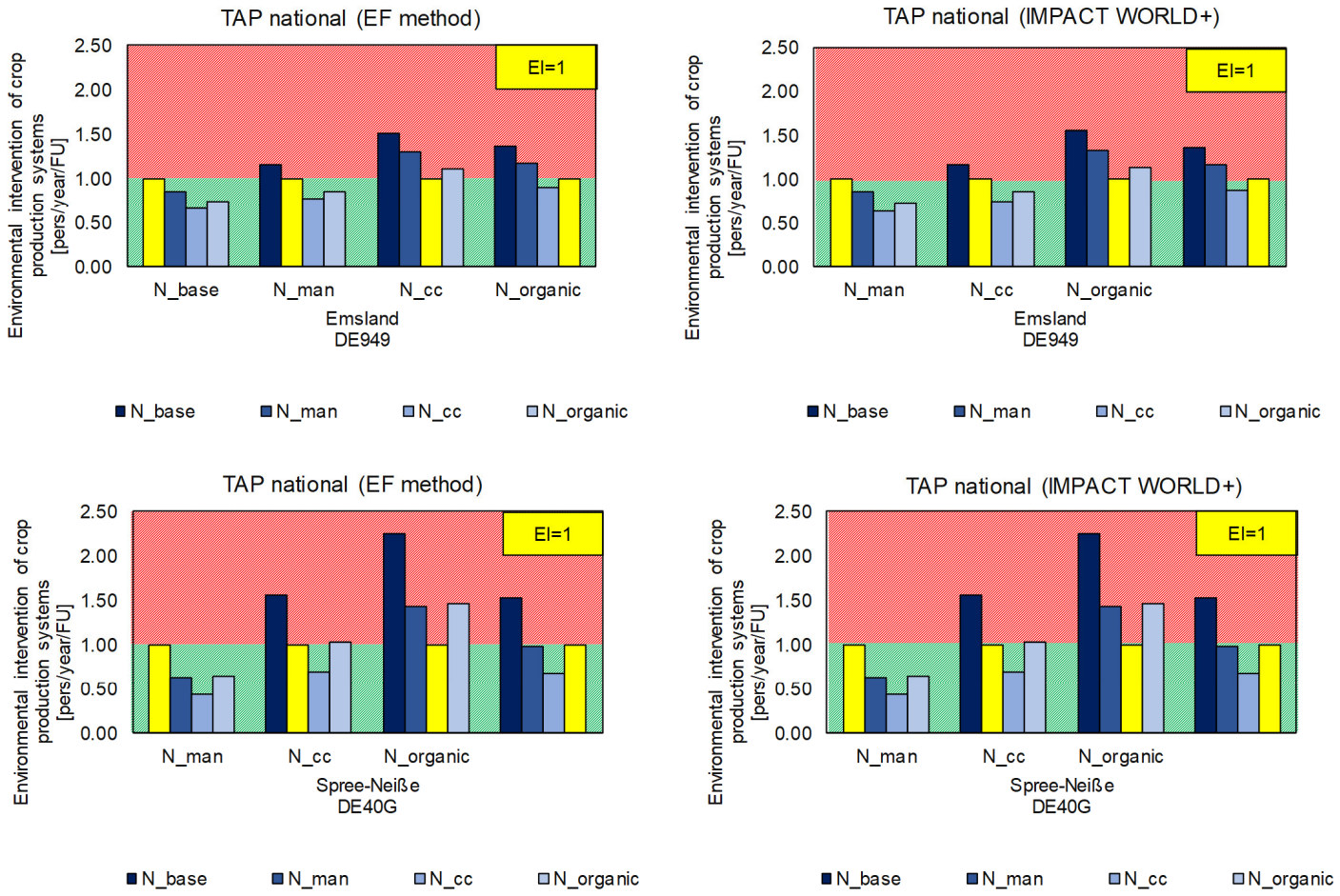

Figure S3. Environmental intervention calculated with national CF for terrestrial acidification impacts (TAP) if EI (Environmental intervention) is set 1. (EF = Environmental Footprint, CF = Characterization factor, Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario)

Table S1. Results of LCA Monte Carlo analysis for all regions and scenarios. (CI = Confidence interval, SD = Standard deviation)

						LCIA results		Monte Carlo Analysis LCIA results				
Region	**NUTS-ID**	**LCIA method**	**Impact category**	**Unit**	**Scenario**	**LCIA result**	**Unit**	**CI 95% probability range**		**SD**	**Mean**	**Median**
Ansbach	DE256	IMPACT World + (regional)	TAP	kg SO_2 eq/pers/year	N_base	2.15E-01	kg SO_2 eq/ha	2.15E-01	2.21E-01	1.18E-02	2.17E-01	2.17E-01
					N_man	1.72E-01	kg SO_2 eq/ha	1.68E-01	2.51E-01	1.20E+01	-2.06E-01	1.74E-01
					N_cc	1.22E-01	kg SO_2 eq/ha	1.20E-01	1.79E-01	9.24E-02	1.37E-01	1.25E-01
					N_organic	1.61E-01	kg SO_2 eq/ha	1.60E-01	1.65E-01	1.11E-02	1.62E-01	1.62E-01
		EF 2.0, national	TEP	mole N-eq/pers/year	N_base	2.05E+02	mole N-eq/ha	2.03E+02	2.14E+02	4.47E+00	2.08E+02	2.08E+02
					N_man	1.64E+02	mole N-eq/ha	1.60E+02	2.47E+02	9.91E+02	2.15E+02	1.68E+02
					N_cc	1.21E+02	mole N-eq/ha	1.18E+02	1.81E+02	2.79E+02	1.21E+02	1.25E+02
					N_organic	1.53E+02	mole N-eq/ha	1.52E+02	1.59E+02	3.17E+00	1.55E+02	1.55E+02
		EF 2.0, national	TAP	mole H^+/pers/year	N_base	6.76E+01	mole H+/ha	6.72E+01	7.16E+01	2.23E+00	6.91E+01	6.90E+01
					N_man	5.46E+01	mole H+/ha	5.34E+01	8.16E+01	3.27E+02	7.18E+01	5.63E+01
					N_cc	4.09E+01	mole H+/ha	3.98E+01	6.09E+01	9.52E+01	4.10E+01	4.24E+01
					N_organic	5.02E+01	mole H+/ha	5.00E+01	5.28E+01	1.57E+00	5.12E+01	5.12E+01
Spree-Neiße	DE40G	IMPACT World + (regional)	TAP	kg SO_2 eq/pers/year	N_base	1.74E-01	kg SO_2 eq/ha	1.74E-01	1.81E-01	1.27E-02	1.77E-01	1.77E-01
					N_man	1.11E-01	kg SO_2 eq/ha	1.10E-01	1.17E-01	6.00E-03	1.13E-01	1.13E-01
					N_cc	7.77E-02	kg SO_2 eq/ha	7.67E-02	8.23E-02	7.32E-03	7.91E-02	7.90E-02
					N_organic	1.14E-01	kg SO_2 eq/ha	1.13E-01	1.17E-01	5.56E-03	1.15E-01	1.15E-01
		EF 2.0, national	TEP	mole N-eq/pers/year	N_base	2.01E+02	mole N-eq/ha	1.98E+02	2.10E+02	4.83E+00	2.04E+02	2.04E+02
					N_man	1.27E+02	mole N-eq/ha	1.25E+02	1.35E+02	3.61E+00	1.30E+02	1.29E+02
					N_cc	9.13E+01	mole N-eq/ha	8.95E+01	9.77E+01	3.09E+00	9.33E+01	9.31E+01
					N_organic	1.29E+02	mole N-eq/ha	1.27E+02	1.33E+02	2.09E+00	1.30E+02	1.30E+02
		EF 2.0, national	TAP	mole H^+/pers/year	N_base	6.61E+01	mole H+/ha	6.57E+01	7.04E+01	2.31E+00	6.76E+01	6.75E+01
					N_man	4.21E+01	mole H+/ha	4.16E+01	4.52E+01	1.50E+00	4.31E+01	4.30E+01
					N_cc	3.05E+01	mole H+/ha	3.01E+01	3.30E+01	1.37E+00	3.14E+01	3.13E+01
					N_organic	4.18E+01	mole H+/ha	4.14E+01	4.33E+01	9.28E-01	4.23E+01	4.23E+01

Continuation table S1. Results of LCA Monte Carlo analysis for all regions and scenarios. (CI = Confidence interval, SD = Standard deviation)

						LCIA results		Monte Carlo Analysis LCIA results				
Region	**NUTS-ID**	**LCIA method**	**Impact category**	**Unit**	**Scenario**	**LCIA result**	**Unit**	**CI 95% probability range**		**SD**	**Mean**	**Median**
Kassel	DE734	IMPACT World + (regional)	TAP	kg SO_2eq/pers/year	N_base	8.08E-02	kg SO_2 eq/ha	8.00E-02	8.77E-02	1.26E-02	8.33E-02	8.33E-02
					N_man	6.43E-02	kg SO_2 eq/ha	6.34E-02	7.69E-02	7.26E-02	6.58E-02	6.69E-02
					N_cc	5.09E-02	kg SO_2 eq/ha	5.03E-02	6.05E-02	1.45E-01	4.99E-02	5.34E-02
					N_organic	1.04E-01	kg SO_2 eq/ha	1.04E-01	1.09E-01	1.11E-02	1.06E-01	1.06E-01
		EF 2.0, national	TEP	mole N-eq/pers/year	N_base	1.05E+02	mole N-eq/ha	1.01E+02	1.16E+02	5.48E+00	1.08E+02	1.08E+02
					N_man	8.27E+01	mole N-eq/ha	7.97E+01	1.00E+02	2.02E+01	8.80E+01	8.66E+01
					N_cc	6.75E+01	mole N-eq/ha	6.55E+01	8.02E+01	1.40E+01	7.11E+01	7.07E+01
					N_organic	1.24E+02	mole N-eq/ha	1.22E+02	1.30E+02	3.26E+00	1.26E+02	1.26E+02
		EF 2.0, national	TAP	mole H^+/pers/year	N_base	3.56E+01	mole H+/ha	3.49E+01	4.03E+01	2.43E+00	3.72E+01	3.71E+01
					N_man	2.85E+01	mole H+/ha	2.79E+01	3.57E+01	6.94E+00	3.07E+01	3.01E+01
					N_cc	2.36E+01	mole H+/ha	2.31E+01	2.86E+01	5.27E+00	2.51E+01	2.50E+01
					N_organic	4.07E+01	mole H+/ha	4.04E+01	4.34E+01	1.55E+00	4.16E+01	4.16E+01
Mecklenburgische Seenplatte	DE80J	IMPACT World + (regional)	TAP	kg SO_2eq/pers/year	N_base	2.77E-01	kg SO_2 eq/ha	2.77E-01	2.83E-01	1.20E-02	2.79E-01	2.79E-01
					N_man	2.77E-01	kg SO_2 eq/ha	2.76E-01	2.83E-01	1.16E-02	2.79E-01	2.79E-01
					N_cc	2.26E-01	kg SO_2 eq/ha	2.26E-01	2.32E-01	1.32E-02	2.28E-01	2.28E-01
					N_organic	2.35E-01	kg SO_2 eq/ha	2.35E-01	2.40E-01	1.19E-02	2.37E-01	2.37E-01
		EF 2.0, national	TEP	mole N-eq/pers/year	N_base	3.45E+02	mole N-eq/ha	3.43E+02	3.53E+02	4.50E+00	3.48E+02	3.48E+02
					N_man	3.45E+02	mole N-eq/ha	3.43E+02	3.54E+02	4.53E+00	3.48E+02	3.48E+02
					N_cc	2.83E+02	mole N-eq/ha	2.82E+02	2.92E+02	4.41E+00	2.86E+02	2.86E+02
					N_organic	2.94E+02	mole N-eq/ha	2.93E+02	3.01E+02	3.66E+00	2.97E+02	2.97E+02
		EF 2.0, national	TAP	mole H^+/pers/year	N_base	1.12E+02	mole H+/ha	1.12E+02	1.16E+02	2.29E+00	1.13E+02	1.13E+02
					N_man	1.12E+02	mole H+/ha	1.11E+02	1.16E+02	2.30E+00	1.13E+02	1.13E+02
					N_cc	9.23E+01	mole H+/ha	9.20E+01	9.60E+01	2.28E+00	9.37E+01	9.36E+01
					N_organic	9.51E+01	mole H+/ha	9.48E+01	9.80E+01	1.87E+00	9.62E+01	9.62E+01

Continuation table S1. Results of LCA Monte Carlo analysis for all regions and scenarios. (CI = Confidence interval, SD = Standard deviation)

						LCIA results		Monte Carlo Analysis LCIA results				
Region	**NUTS-ID**	**LCIA method**	**Impact category**	**Unit**	**Scenario**	**LCIA result**	**Unit**	**CI 95% probability range**		**SD**	**Mean**	**Median**
Emsland	DE949	IMPACT World + (regional)	TAP	kg SO_2eq/pers/year	N_base	3.45E-02	kg SO_2 eq/ha	3.41E-02	4.05E-02	1.20E-02	3.67E-02	3.67E-02
					N_man	3.06E-02	kg SO_2 eq/ha	3.00E-02	4.05E-02	2.79E-02	3.44E-02	3.29E-02
					N_cc	2.81E-02	kg SO_2 eq/ha	2.76E-02	3.67E-02	2.28E-02	3.08E-02	3.03E-02
					N_organic	2.62E-02	kg SO_2 eq/ha	2.58E-02	3.01E-02	1.04E-02	2.75E-02	2.76E-02
		EF 2.0, national	TEP	mole N-eq/pers/year	N_base	2.50E+02	mole N-eq/ha	2.48E+02	2.58E+02	4.25E+00	2.52E+02	2.52E+02
					N_man	2.14E+02	mole N-eq/ha	2.09E+02	2.83E+02	4.55E+02	2.45E+02	2.17E+02
					N_cc	1.63E+02	mole N-eq/ha	1.59E+02	2.07E+02	3.44E+02	1.66E+02	1.66E+02
					N_organic	1.85E+02	mole N-eq/ha	1.84E+02	1.91E+02	2.92E+00	1.87E+02	1.87E+02
		EF 2.0, national	TAP	mole H^+/pers/year	N_base	8.18E+01	mole H+/ha	8.14E+01	8.55E+01	2.17E+00	8.32E+01	8.31E+01
					N_man	7.02E+01	mole H+/ha	6.88E+01	9.32E+01	1.49E+02	8.08E+01	7.17E+01
					N_cc	5.40E+01	mole H+/ha	5.28E+01	6.87E+01	1.14E+02	5.50E+01	5.53E+01
					N_organic	6.02E+01	mole H+/ha	6.00E+01	6.25E+01	1.46E+00	6.11E+01	6.10E+01

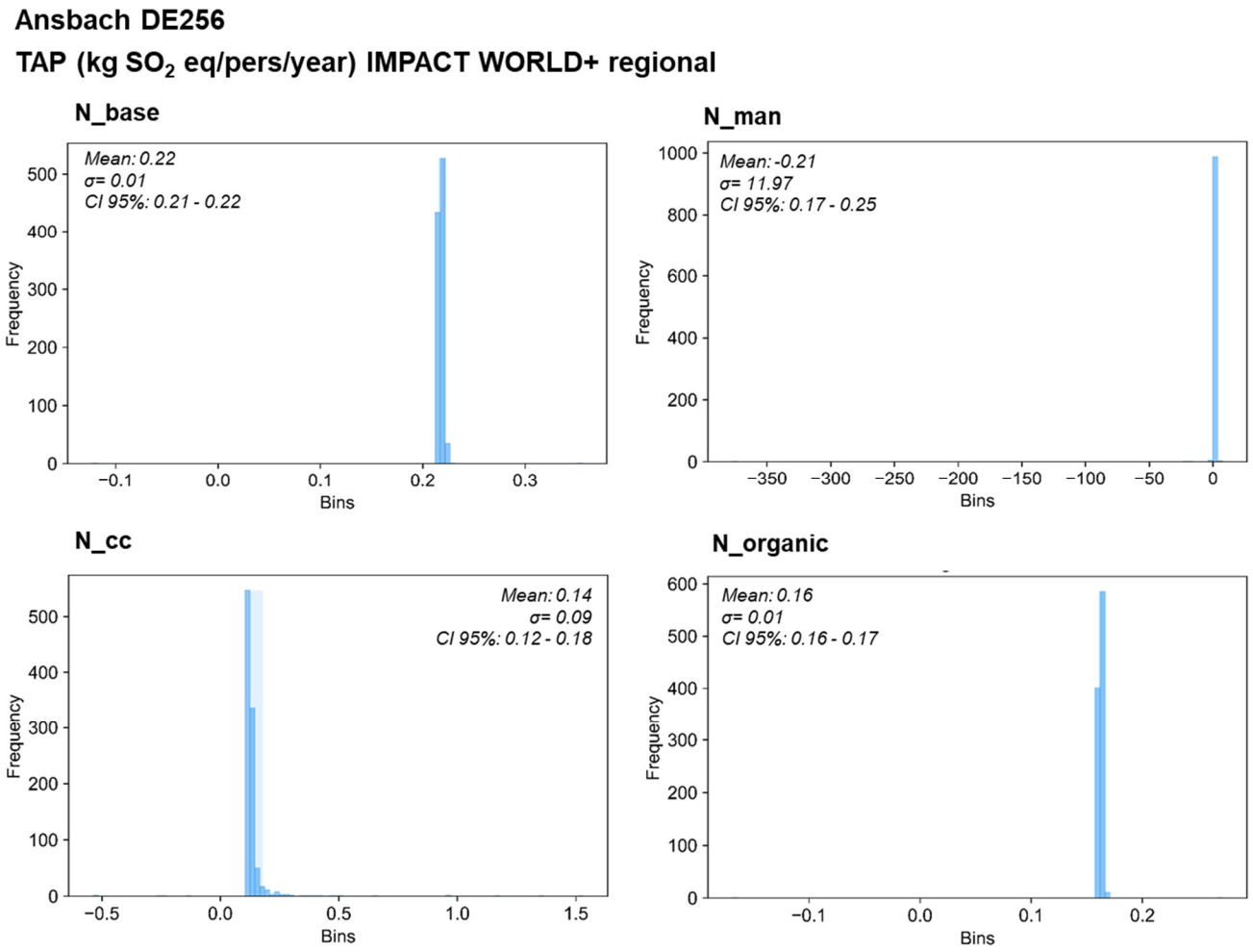

Figure S4. LCA Monte Carlo analysis of all scenarios in the region Ansbach for Terrestrial acidification potential (TAP, regional). Figure shows mean, CI = Confidence interval and standard deviation.

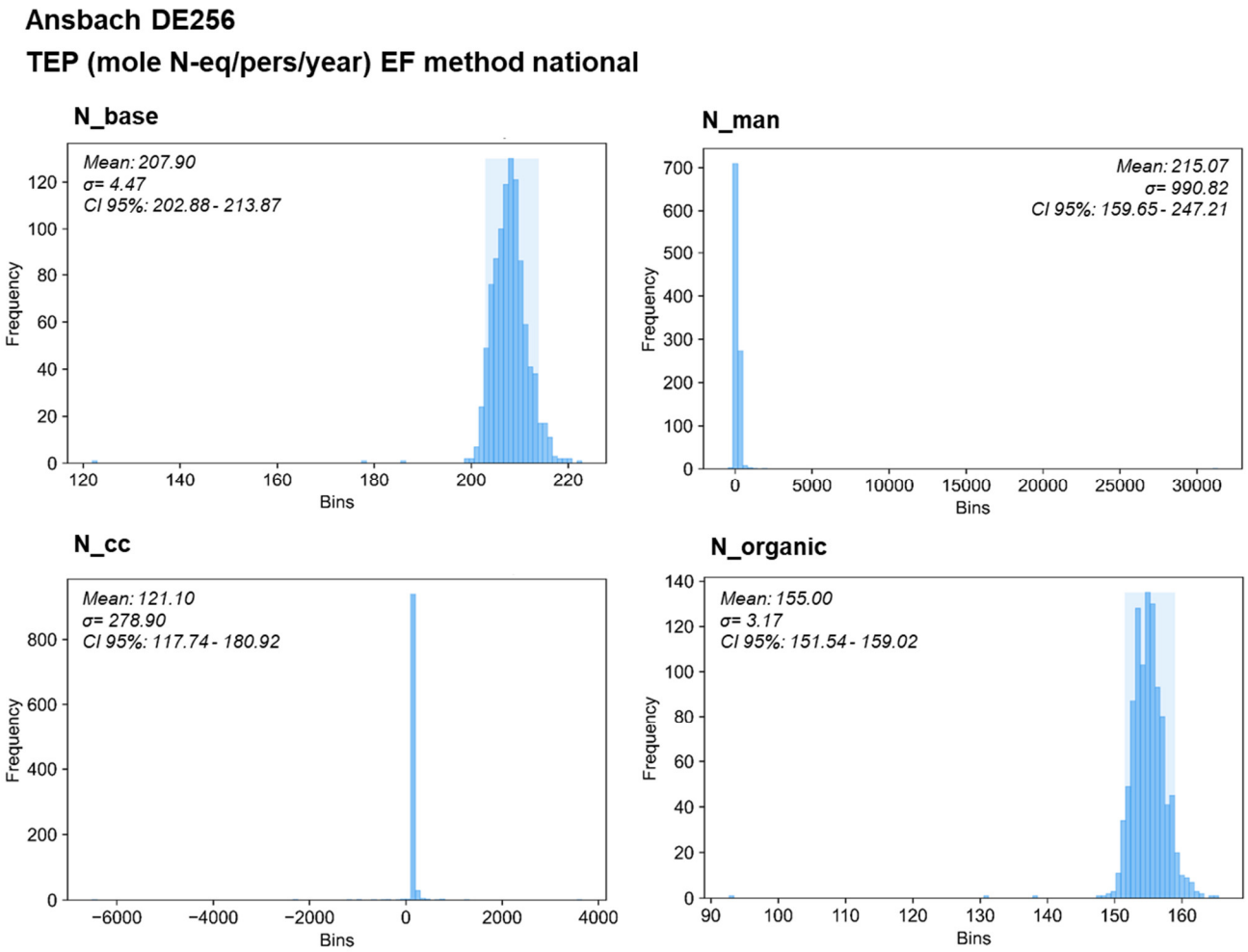

Figure S5. LCA Monte Carlo analysis of all scenarios in the region Ansbach for Terrestrial eutrophication potential (TEP, national). Figure shows mean, CI = Confidence interval and standard deviation.

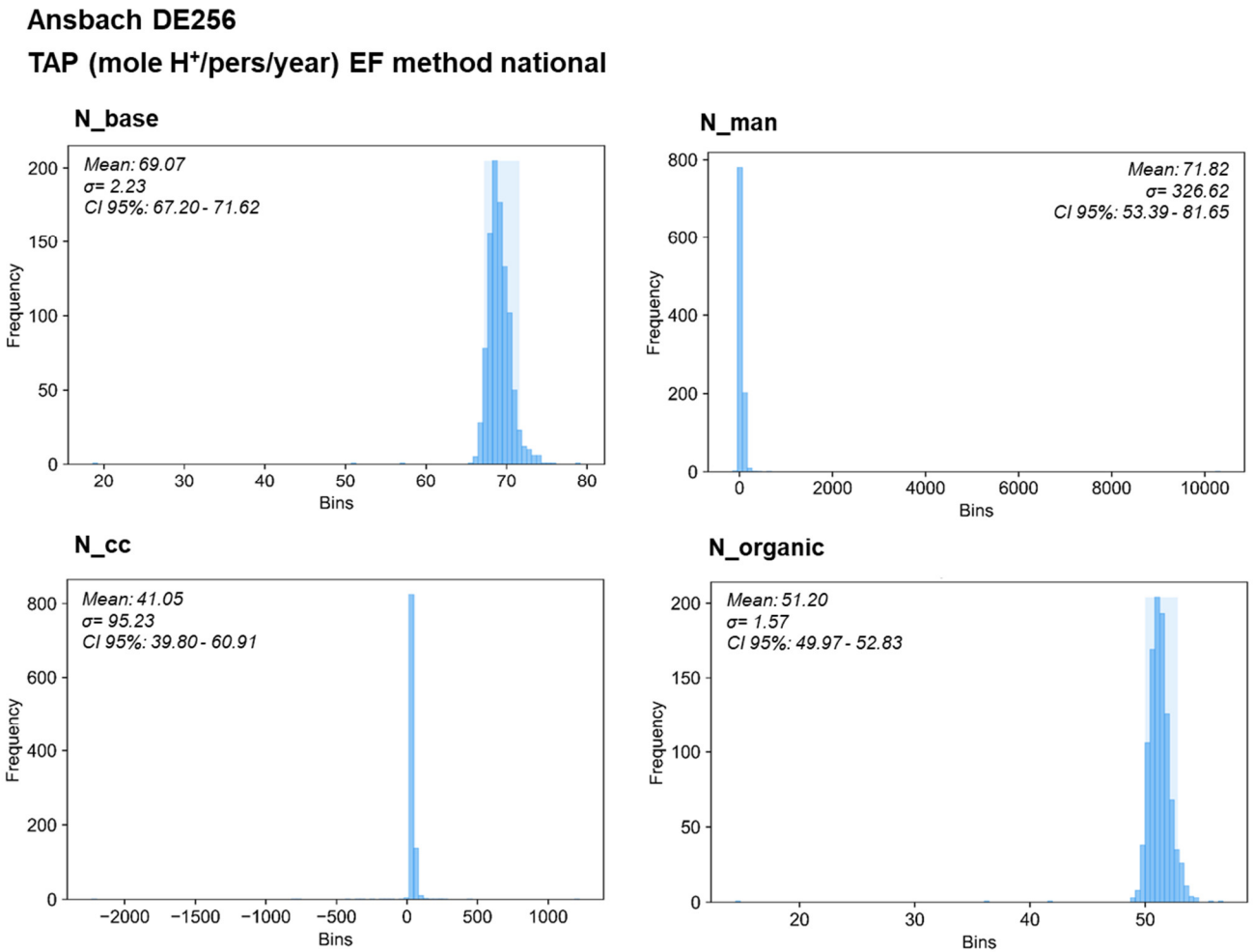

Figure S6. LCA Monte Carlo analysis of all scenarios in the region Ansbach for Terrestrial acidification potential (TAP, national). Figure shows mean, CI = Confidence interval and standard deviation.

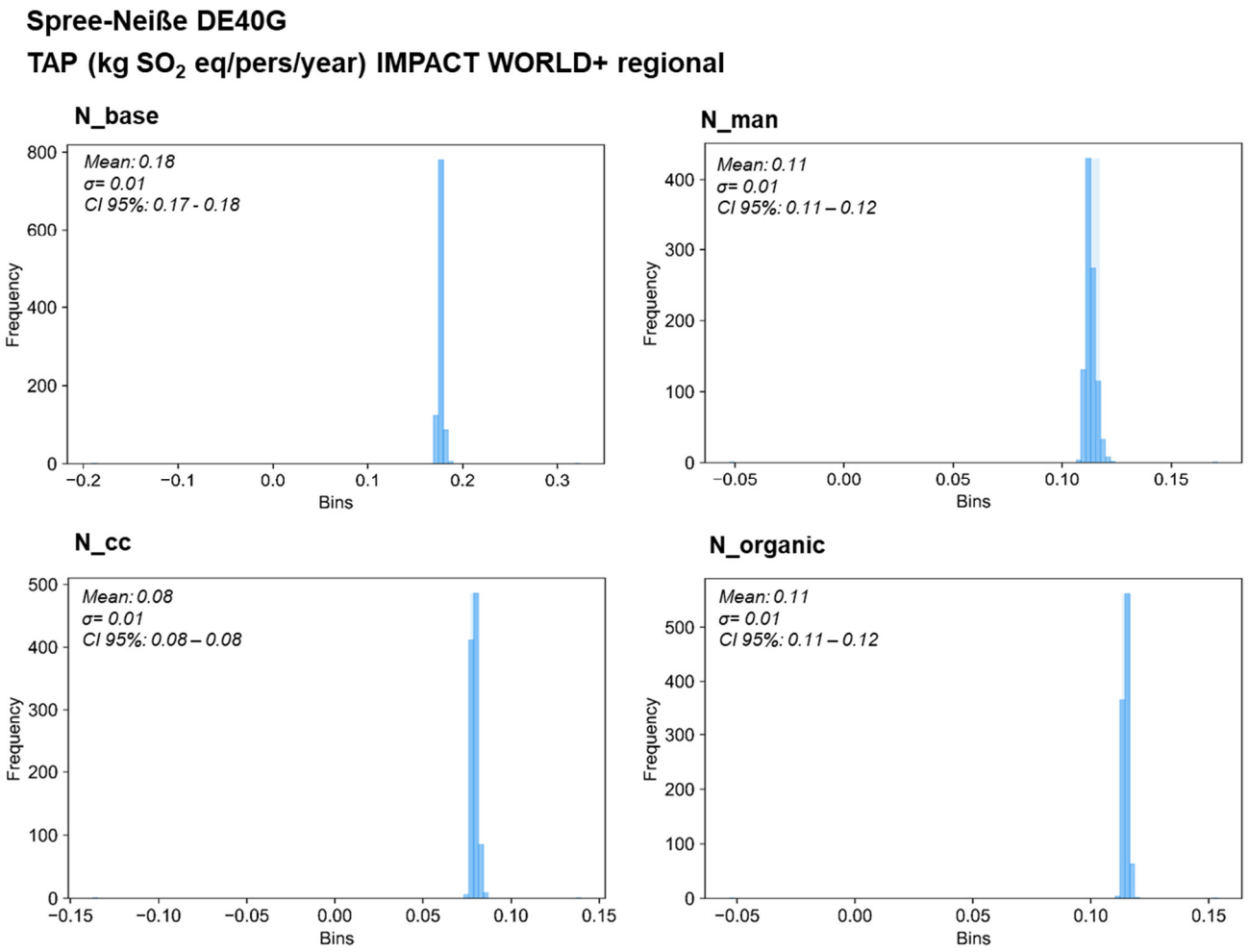

Figure S7. LCA Monte Carlo analysis of all scenarios in the region Spree-Neiße for Terrestrial acidification potential (TAP, regional). Figure shows mean, CI = Confidence interval and standard deviation.

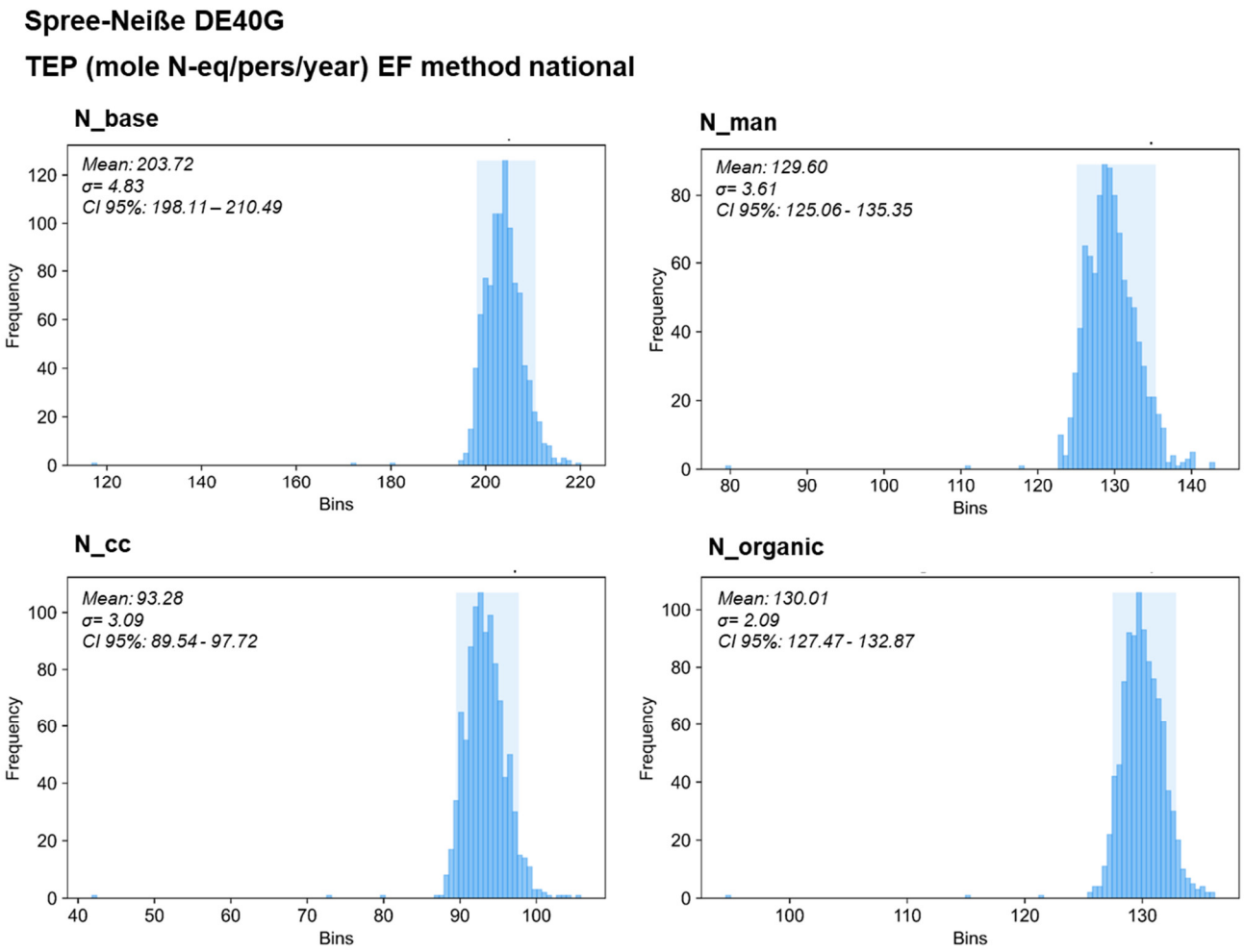

Figure S8. LCA Monte Carlo analysis of all scenarios in the region Spree-Neiße for Terrestrial eutrophication potential (TEP, national). Figure shows mean, CI = Confidence interval and standard deviation.

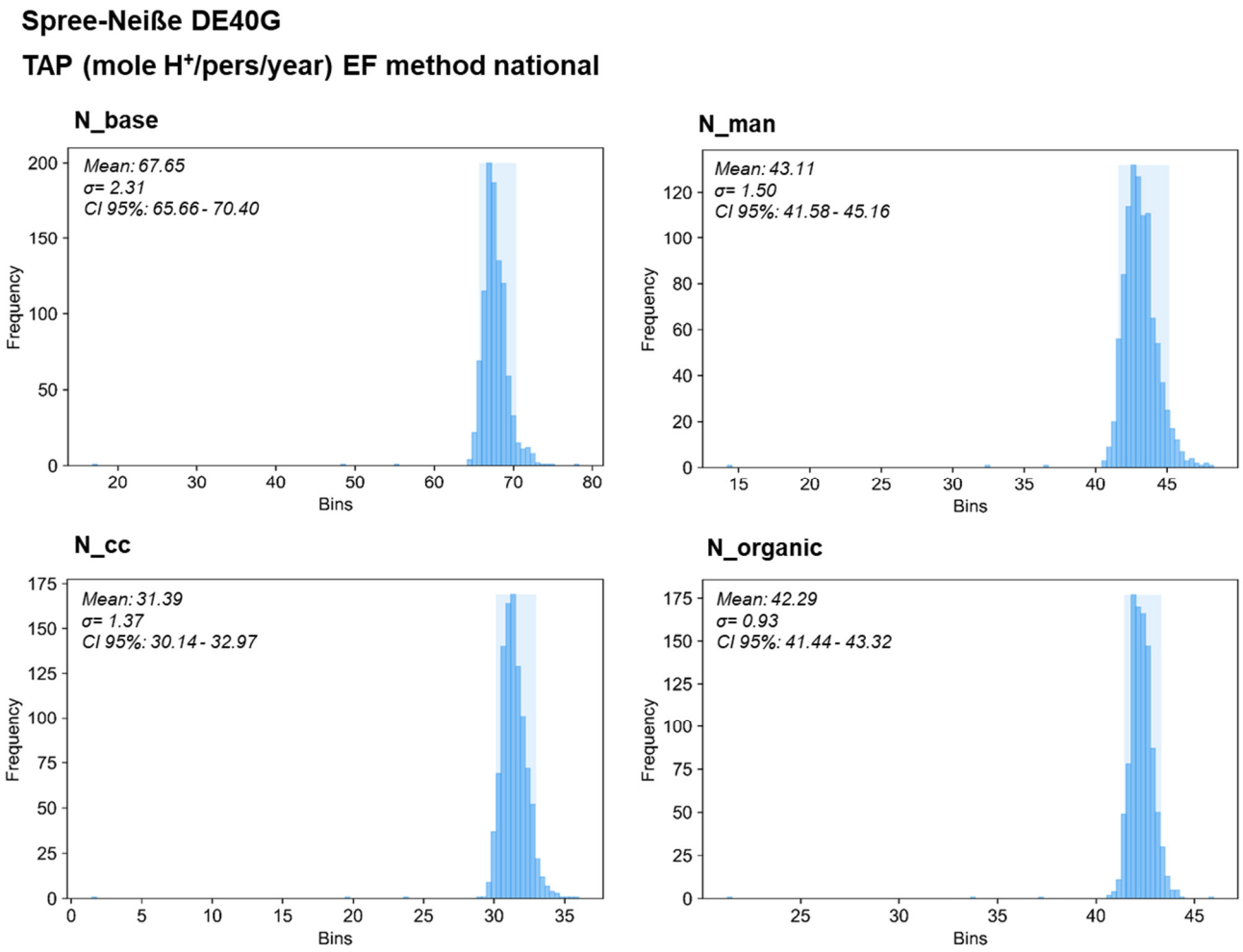

Figure S9. LCA Monte Carlo analysis of all scenarios in the region Spree-Neiße for Terrestrial acidification potential (TAP, national). Figure shows mean, CI = Confidence interval and standard deviation.

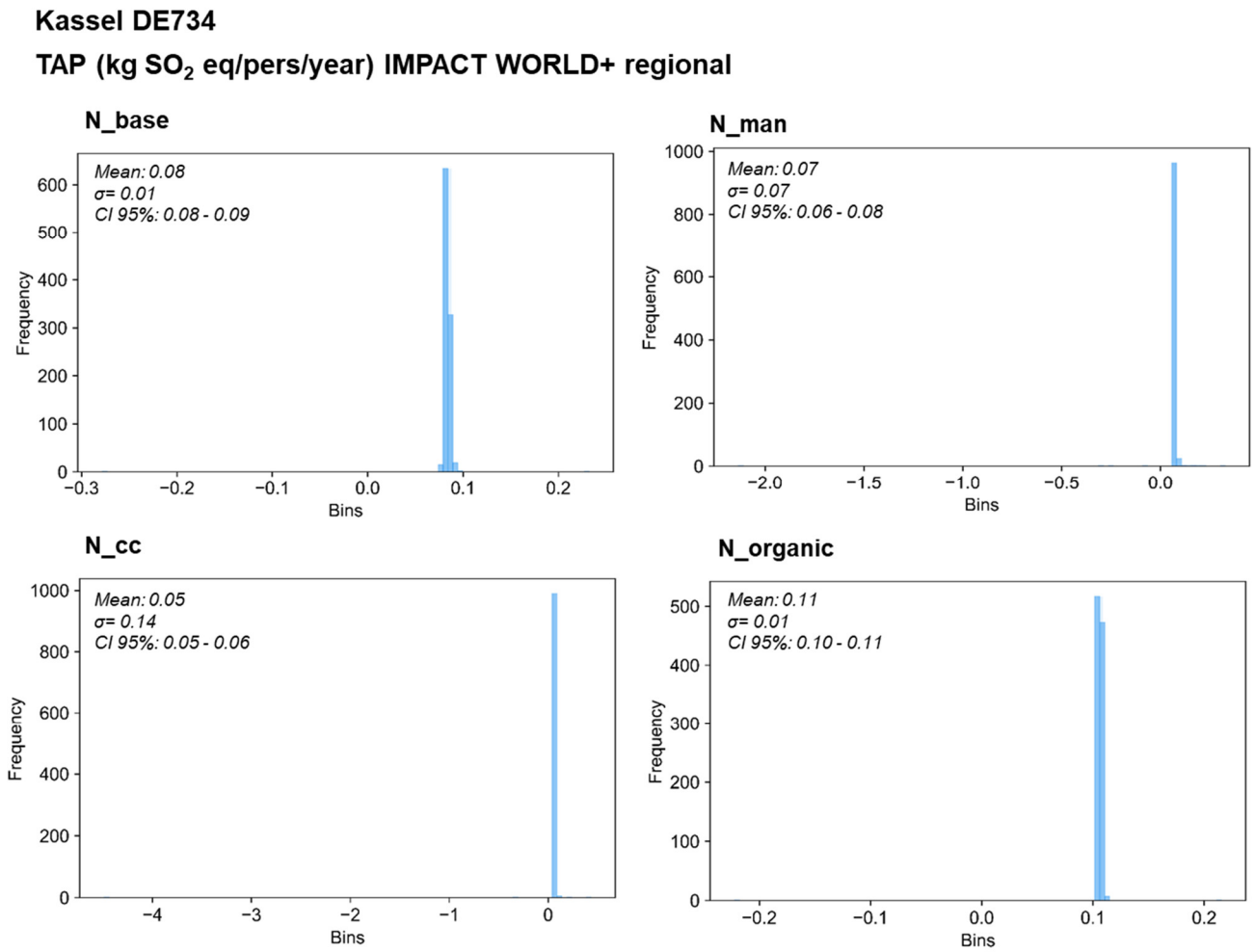

Figure S10. LCA Monte Carlo analysis of all scenarios in the region Kassel for Terrestrial acidification potential (TAP, regional). Figure shows mean, CI = Confidence interval and standard deviation.

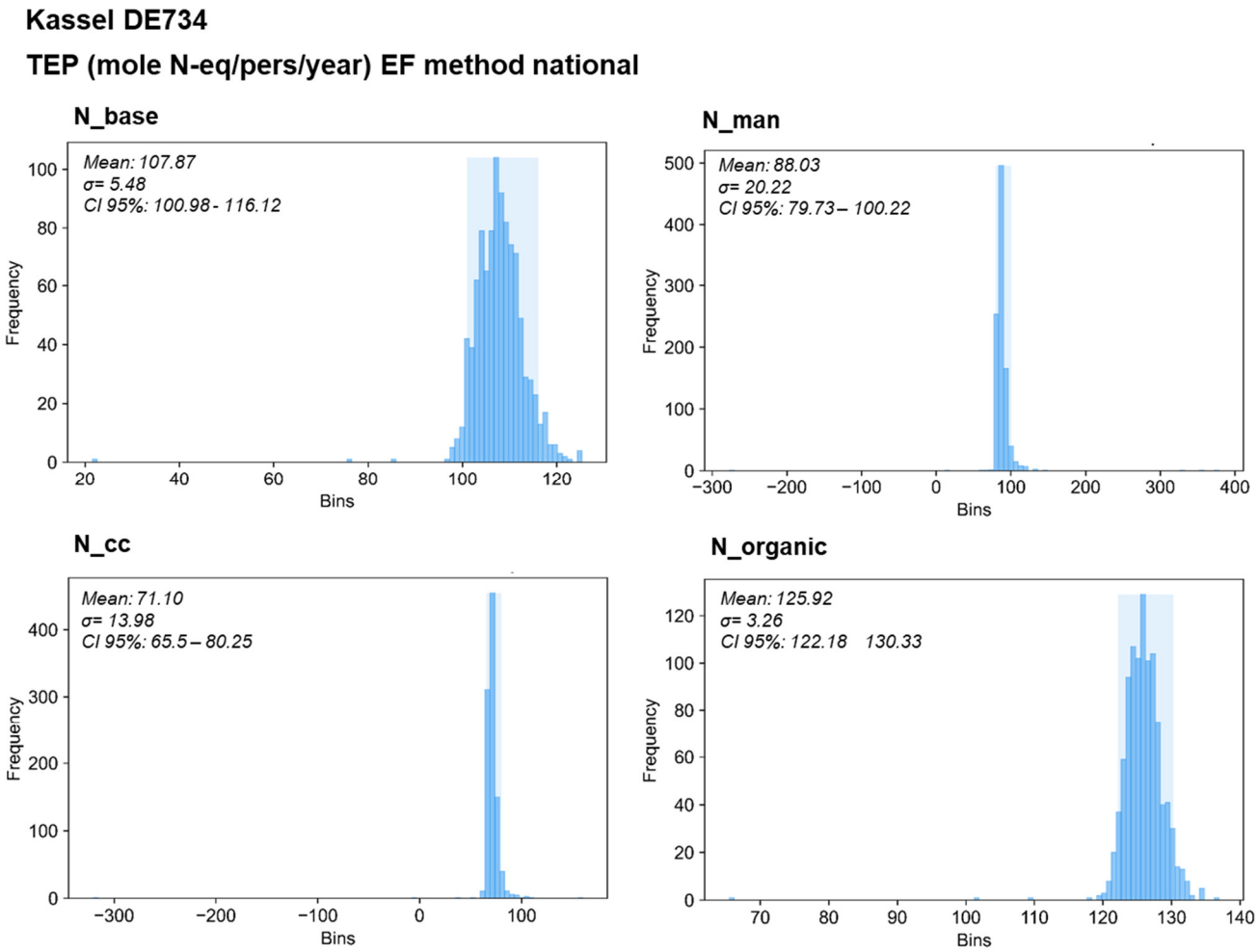

Figure S11. LCA Monte Carlo analysis of all scenarios in the region Kassel for Terrestrial eutrophication potential (TEP, national). Figure shows mean, CI = Confidence interval and standard deviation.

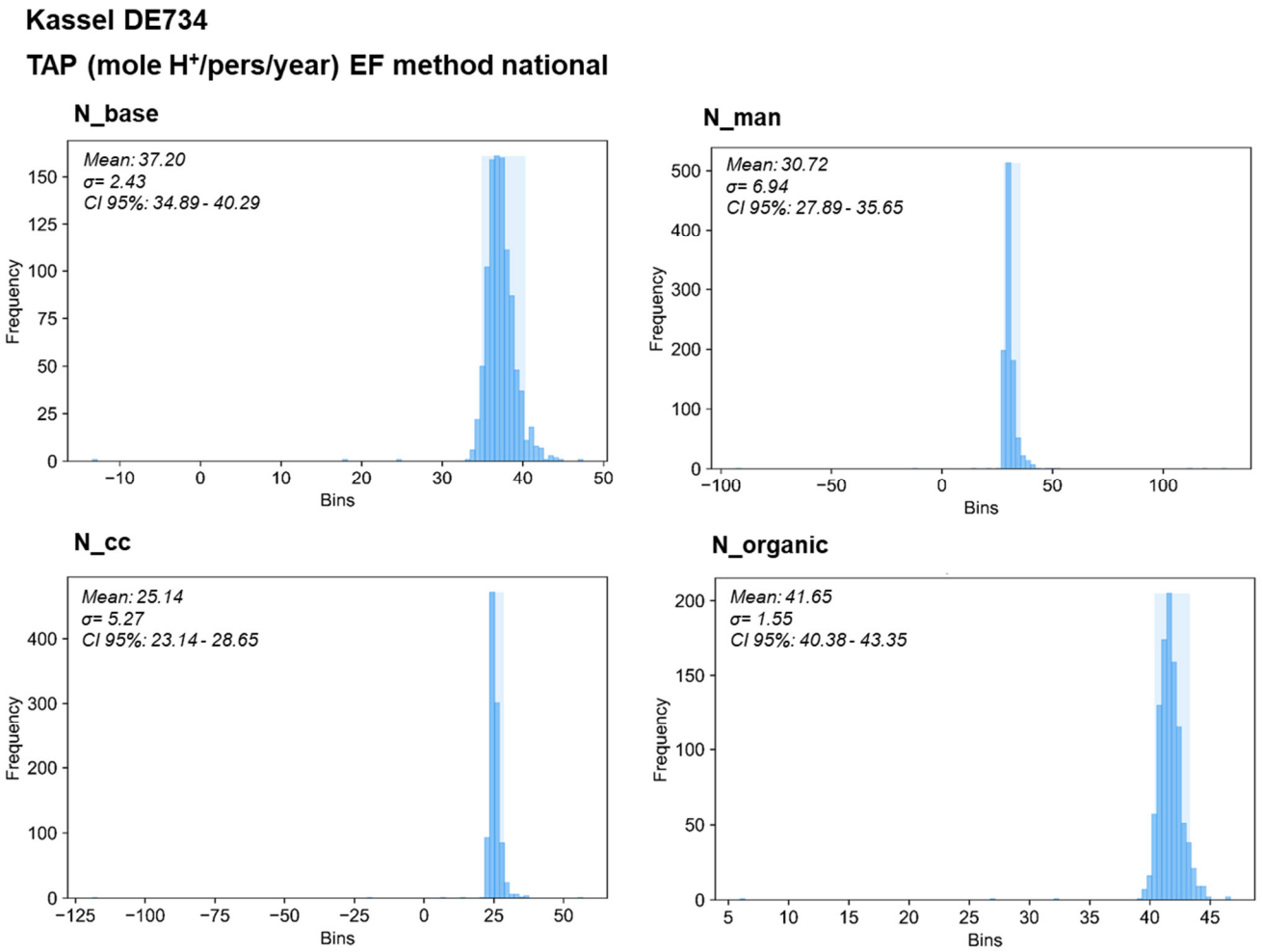

Figure S12. LCA Monte Carlo analysis of all scenarios in the region Kassel for Terrestrial acidification potential (TAP, national). Figure shows mean, CI = Confidence interval and standard deviation.

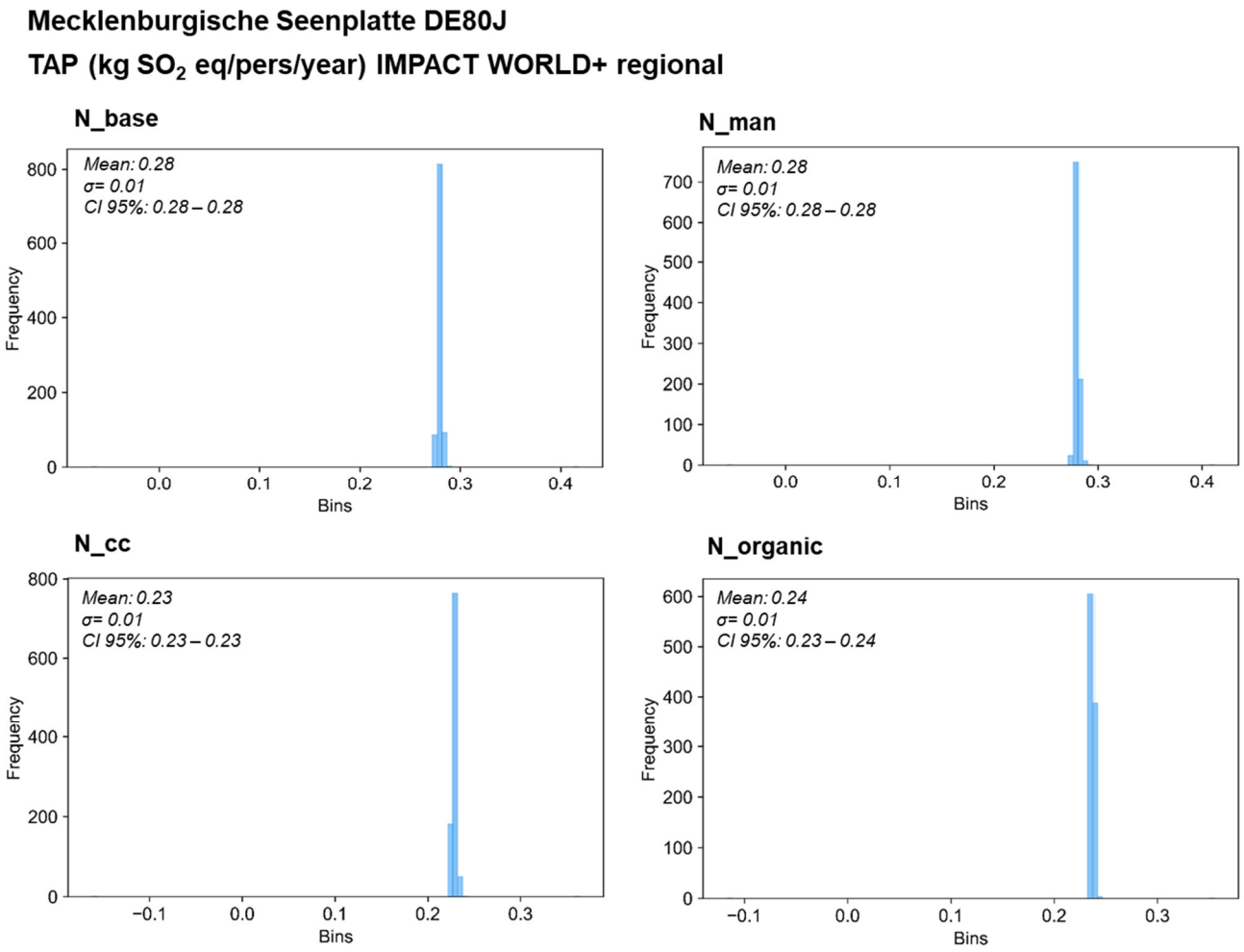

Figure S13. LCA Monte Carlo analysis of all scenarios in the region Mecklenburgische Seenplatte for Terrestrial acidification potential (TAP, regional). Figure shows mean, CI = Confidence interval and standard deviation.

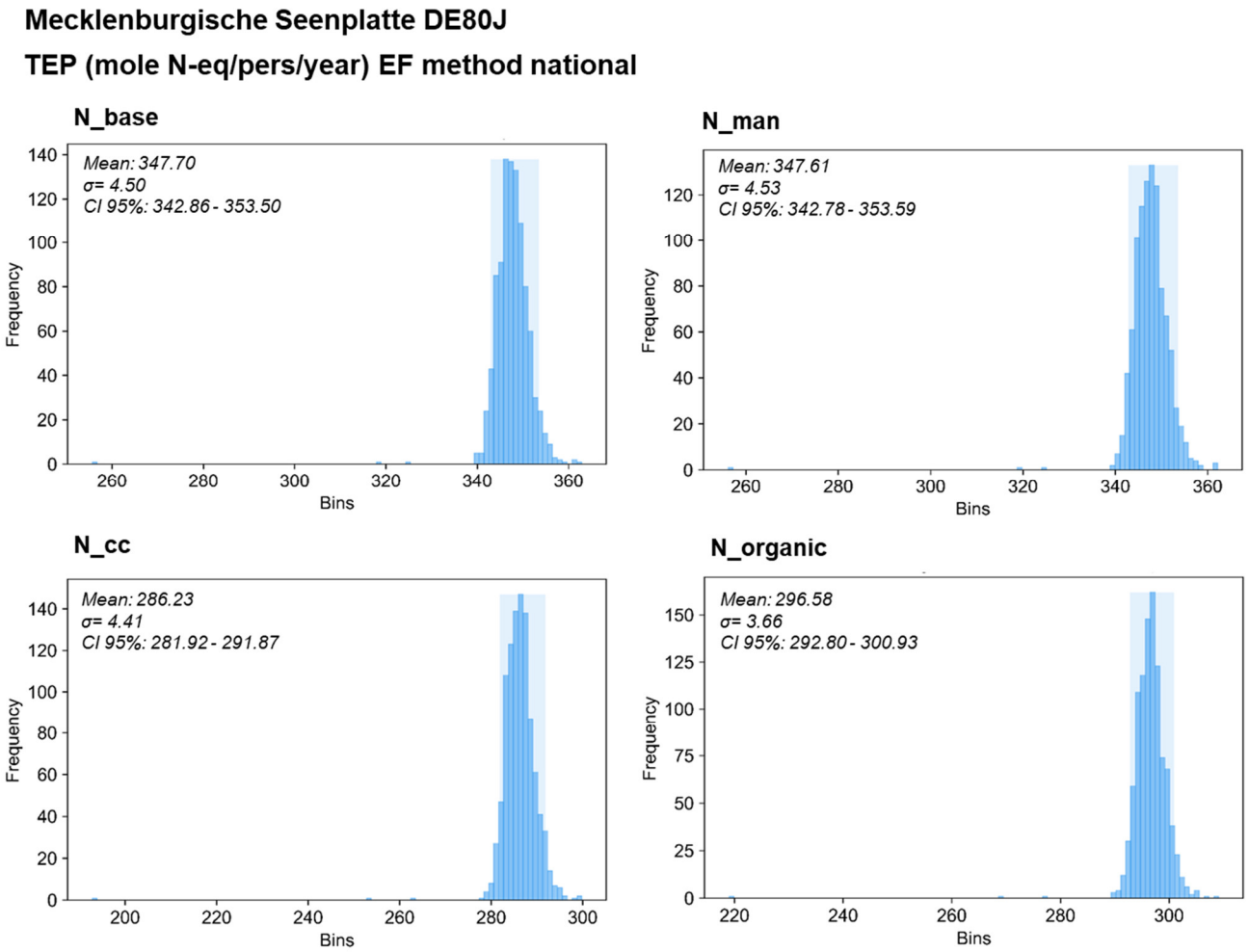

Figure S14. LCA Monte Carlo analysis of all scenarios in the region Mecklenburgische Seenplatte for Terrestrial eutrophication potential (TEP, national). Figure shows mean, CI = Confidence interval and standard deviation.

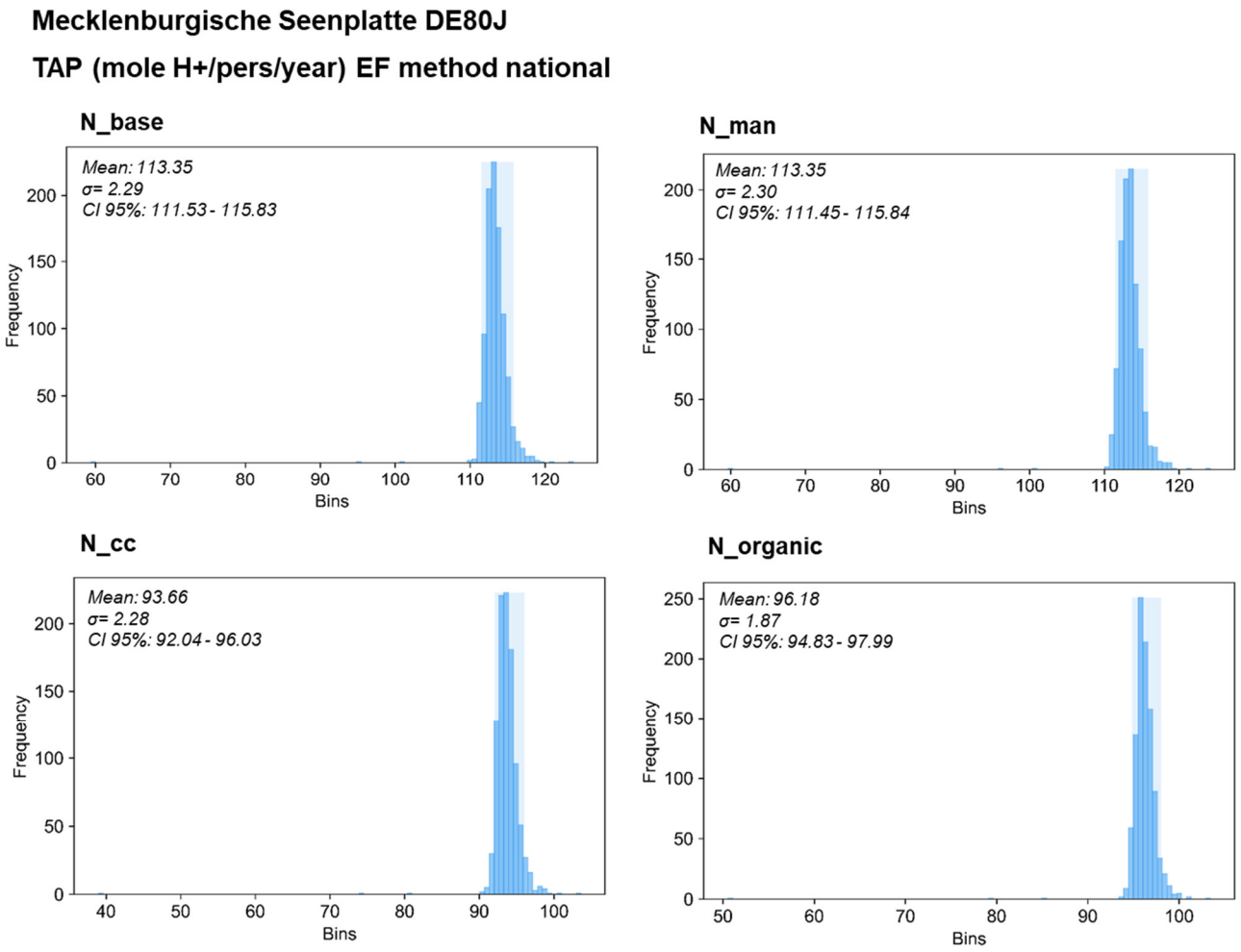

Figure S15. LCA Monte Carlo analysis of all scenarios in the region Mecklenburgische Seenplatte for Terrestrial acidification potential (TAP, national). Figure shows mean, CI = Confidence interval and standard deviation.

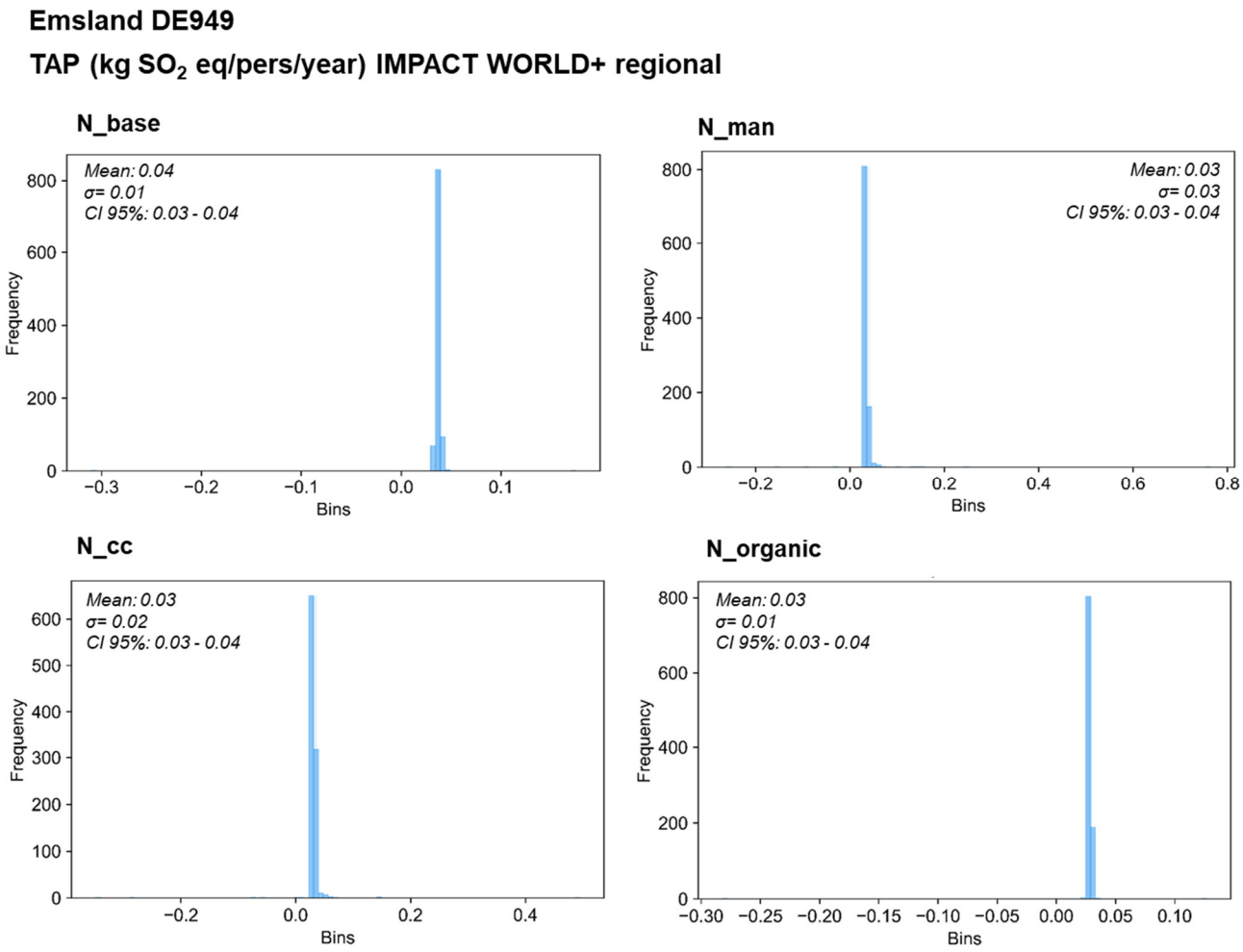

Figure S16. LCA Monte Carlo analysis of all scenarios in the region Emsland for Terrestrial acidification potential (TAP, regional). Figure shows mean, CI = Confidence interval and standard deviation.

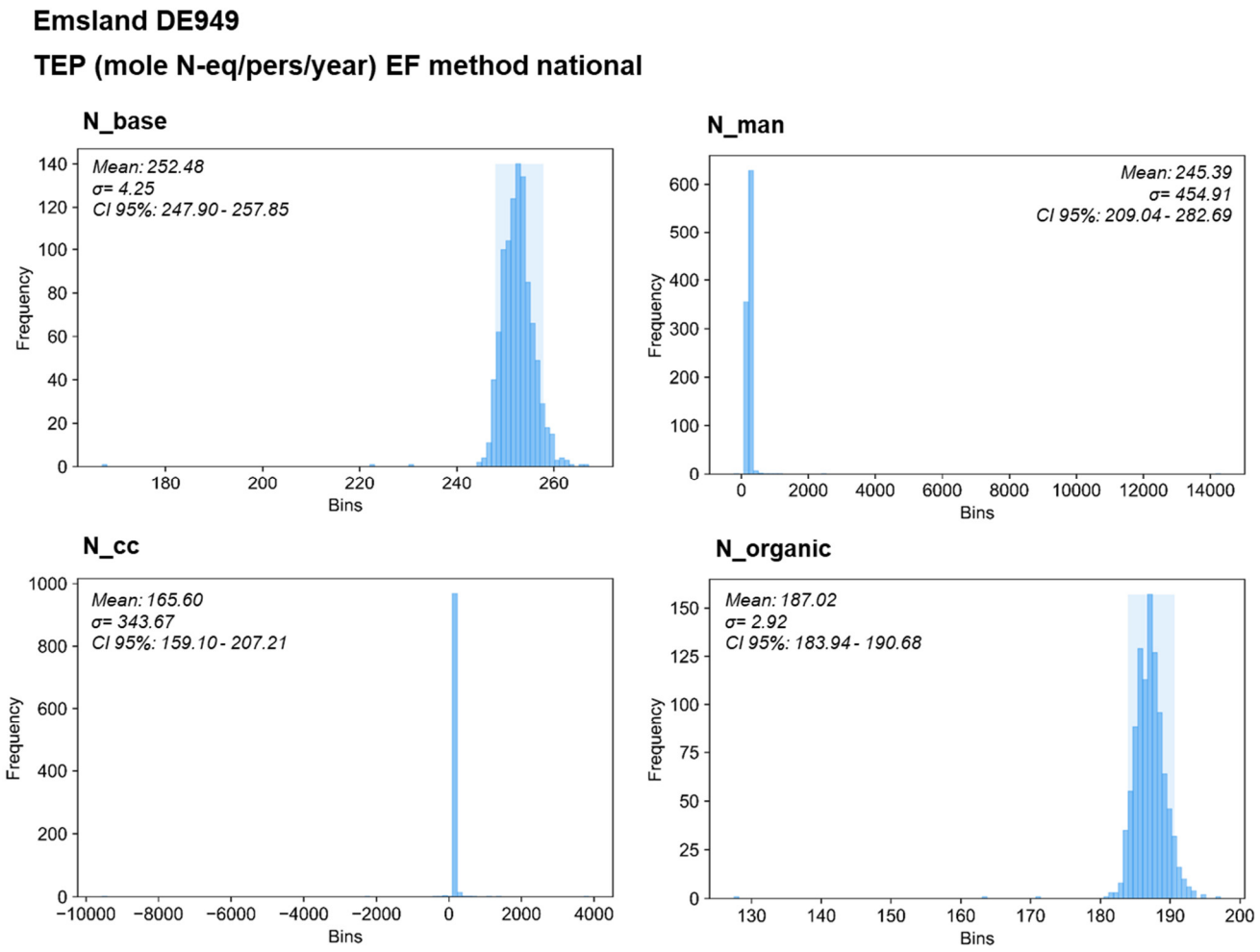

Figure S17. LCA Monte Carlo analysis of all scenarios in the region Emsland for Terrestrial eutrophication potential (TEP, national). Figure shows mean, CI = Confidence interval and standard deviation.

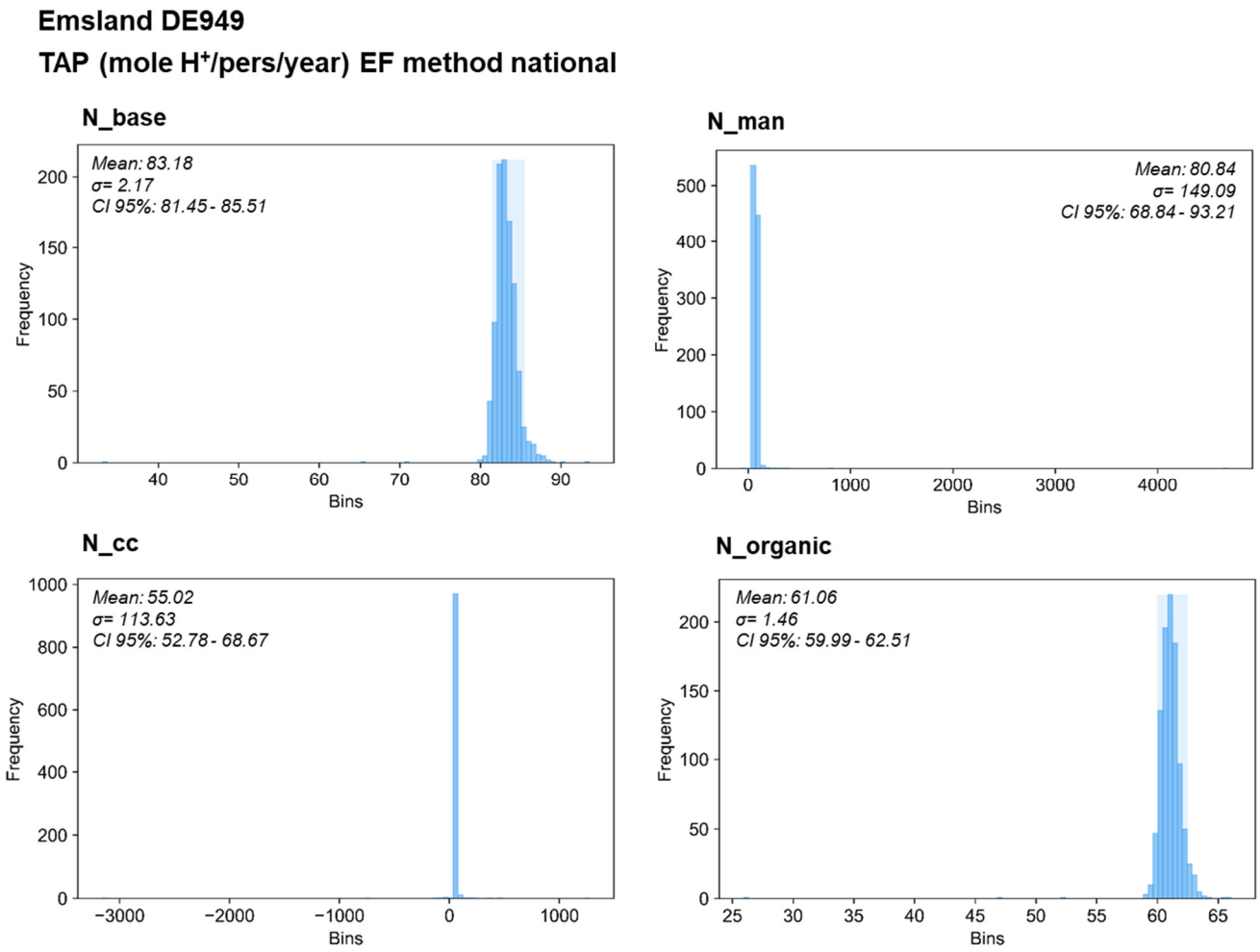

Figure S18. LCA Monte Carlo analysis of all scenarios in the region Emsland for Terrestrial acidification potential (TAP, national). Figure shows mean, CI = Confidence interval and standard deviation.