Supplementary Materials: Species-richness responses to water-withdrawal scenarios and minimum flow levels: Evaluating presumptive standards in Tennessee and Cumberland river basins

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Table S1: Streamflow characteristics and slope and intercept coefficients of ecological limit functions (ELF) for fish groups among ecoregions reported in [1,2].

Ecoregion	Fish Group[1]	Group abbreviation	Streamflow characteristics	Slope	Intercept
			Ecological limit function		
Blue Ridge (BR)	All species	AllSp	AMH10	-8.9	37.1
	Invertivores	Invert	AMH10	-3.3	14.8
	Lithophilic spawners	LithSpawn	AMH10	-4.3	18.2
Ridge and Valley (RV)	All species	AllSp	FL2	-10.9	33.3
	Intolerants	Intolerants	LDH16	-3.1	5.1
	Invertivores	Invert	MA41	-4.7	12.5
	Lithophilic spawners	LithSpawn	FL2	-3.9	13.5
	Natives	Natives	FL2	-13.3	35.1
	Omnivores	Omni	FL2	-0.9	5.2
	Pool dwellers	PoolDwell	FL2	-10.1	25.4
	Specialized insectivores	SpecInsect	LDH16+ TA1	-15.4	18.7
Cumberland Plateau (CP)	All species	AllSp	TL1	-24.3	25.3
	Headwater intolerants	HWIntol	AMH10+ LDH13+ LDL6+ TL1	-2.3	4.4
	Intolerants	Intolerants	AMH10+ ML20+ TL1	-4.9	6.0
	Invertivores	Invert	AMH10	-6.5	7.2
	Lithophilic spawners	LithSpawn	AMH10+ TA1+ TL1	-10.4	18.1
	Natives	Natives	TL1	-31.5	35.0
	Pool dwellers	PoolDwell	TA1+ TL1	-10.4	18.1
	Rare species	RareSp	TA1+ TL1	-2.0	2.3
	Riffle dwellers	RiffDwell	AMH10+ TL1	-3.3	5.3
	Specialized insectivores	SpecInsect	AMH10+ TA1+ TL1	-11.0	15.2
	Top predators	TopPred	MA41+ TL1	-2.0	4.4
Interior Plateau (IP)	All species	AllSp	AMH10+ TL1	-9.9	57.1
	Headwater intolerants	HWIntol	FH6+ TA1	-3.8	9.0
	Intolerants	Intolerants	AMH10+ FH6	-2.3	7.8
	Invertivores	Invert	AMH10+ LRA7+ FH6+TL1	-2.4	19.8
	Lithophilic spawners	LithSpawn	TA1	-32.9	33.1
	Natives	Natives	AMH10+ TA1+ TL1	-8.4	49.6
	Pool dwellers	PoolDwell	AMH10+ TA1+ TL1	-6.0	32.3
	Riffle dwellers	RiffDwell	TA1+ TL1	-4.9	14.1
	Specialized insectivores	SpecInsect	AMH10+ TA1	-5.8	19.6
	Top predators	TopPred	AMH10+ TL1	-1.9	6.6

[1] The identities of fish species within each fish group are not considered in this study and membership of an individual fish species to a fish group is not mutually exclusive. Definitions of fish groups can be found in [1,2]

Table S2. Mean change in species richness across all stream sites and all water-withdrawal scenarios for each fish group and minimum flow level (MFL) under constant-rate and percent-of-flow withdrawals.

Eco-region	Fish group	Streamflow characteristics	Constant-rate withdrawal[1]				Percent-of-flow withdrawal[1]			
			MFL0	MFL5	MFL10	MFL30	MFL0	MFL5	MFL10	MFL30
BR	AllSp	AMH10	-0.28	-0.28	-0.28	-0.26	-0.40	-0.40	-0.40	-0.39
	Invert	AMH10	-0.10	-0.10	-0.10	-0.09	-0.14	-0.14	-0.14	-0.14
	LithSpawn	AMH10	-0.13	-0.13	-0.13	-0.12	-0.19	-0.19	-0.19	-0.19
RV	AllSp	FL2	-0.10	-4.89	-5.57	-1.01	0.00	0.00	-0.19	-0.85
	Intolerants	LDH16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Invert	MA41	-0.82	-0.77	-0.70	-0.49	-0.41	-0.41	-0.41	-0.35
	LithSpawn	FL2	-0.04	-2.00	-2.23	-0.41	0.00	0.00	-0.07	-0.33
	Natives	FL2	-0.08	-5.07	-5.77	-1.07	0.00	0.00	-0.24	-0.91
	Omni	FL2	-0.01	-0.77	-0.77	-0.11	0.00	0.00	-0.02	-0.08
	PoolDwell	FL2	-0.05	-3.65	-4.15	-0.78	0.00	0.00	-0.18	-0.66
	SpecInsect	LDH16+ TA1	-0.71	0.94	1.11	0.15	0.51	0.67	0.81	-0.29
CP	AllSp	TL1	-12.69	-0.02	0.00	0.00	0.00	-0.09	0.00	0.00
	HWIntol	AMH10+ LDH13+ LDL6+ TL1	-1.77	-0.19	-0.18	0.01	-0.04	-0.05	-0.04	0.05
	Intolerants	AMH10+ ML20+ TL1	-2.72	-0.40	-0.34	-0.21	-0.44	-0.42	-0.38	-0.23
	Invert	AMH10	-0.06	-0.05	-0.05	-0.04	-0.08	-0.07	-0.07	-0.06
	LithSpawn	AMH10+ TA1+ TL1	-7.20	0.10	-0.01	0.02	-0.31	-0.22	-0.09	0.00
	Natives	TL1	-17.65	-0.03	0.00	0.00	0.00	-0.12	0.00	0.00
	PoolDwell	TA1+ TL1	-7.63	0.20	0.08	0.10	-0.18	-0.08	0.04	0.14
	RareSp	TA1+ TL1	-0.86	0.04	0.01	0.01	-0.03	-0.01	0.00	0.02
	RiffDwell	AMH10+ TL1	-2.57	-0.03	-0.02	-0.02	-0.04	-0.05	-0.04	-0.04
	SpecInsect	AMH10+ TA1+ TL1	-5.54	0.16	0.01	0.04	-0.25	-0.16	-0.07	0.03
	TopPred	MA41+ TL1	-2.21	-0.09	-0.08	-0.06	-0.08	-0.09	-0.08	-0.07
IP	AllSp	AMH10+ TL1	-21.50	-8.13	-2.97	-0.05	-0.09	-0.52	-0.91	-0.08
	HWIntol	FH6+ TA1	0.02	0.43	0.47	0.34	0.05	0.13	0.19	0.03
	Intolerants	AMH10+ FH6	0.01	0.01	0.01	0.07	-0.02	-0.02	-0.02	-0.02
	Invert	AMH10+ LRA7+ FH6+TL1	-6.81	-3.25	-1.59	0.02	-0.01	-0.11	-0.20	0.02
	LithSpawn	TA1	-0.35	3.30	3.51	1.88	0.21	0.95	1.45	0.17
	Natives	AMH10+ TA1+ TL1	-17.79	-6.04	-1.62	0.45	-0.02	-0.20	-0.38	-0.02
	PoolDwell	AMH10+ TA1+ TL1	-11.64	-4.07	-1.11	0.33	-0.01	-0.14	-0.27	-0.01
	RiffDwell	TA1+ TL1	-4.76	-1.99	-0.58	0.29	0.04	-0.03	-0.17	0.03
	SpecInsect	AMH10+ TA1	-0.12	0.53	0.59	0.31	-0.02	0.11	0.21	-0.01
	TopPred	AMH10+ TL1	-2.57	-1.15	-0.48	-0.01	-0.02	-0.10	-0.18	-0.02

[1] Mean values were calculated using the site-specific data within the "Richness_CR.txt" and "Richness_POF.txt" files from [3].

Table S3. Mean loss and mean percent loss in predicted fish species across stream sites at 10- and 20-percent water-withdrawal scenarios under MFL0.

Eco-region	Fish group	Streamflow characteristic(s)	Mean loss in richness (number of taxa)[1]		Mean percent loss in richness (%)[1]	
			10% water withdrawal	20% water withdrawal	10% water withdrawal	20% water withdrawal
BR	AllSp	AMH10	0.32	0.43	0.99	1.32
	Invert	AMH10	0.11	0.16	0.85	1.20
	LithSpawn	AMH10	0.15	0.21	0.96	1.34
RV	AllSp	FL2				
	Intolerants	FL2				
	Invert	FL2	0.43	0.81	3.86	7.31
	LithSpawn	TA1+ LDH16				
	Natives	MA41				
	Omni	FL2				
	PoolDwell	FL2				
	SpecInsect	LDH16	0.34	0.61	10.59	13.19
CP	AllSp	TL1				
	HWIntol	TA1+ TL1	0.02	0.22	1.12	11.44
	Intolerants	AMH10+ TL1	0.18	0.51	5.40	14.88
	Invert	TL1	0.06	0.08	0.98	1.28
	LithSpawn	AMH10+ TA1+ TL1	0.30	0.62	3.88	7.75
	Natives	AMH10				
	PoolDwell	MA41+ TL1	0.17	0.45	1.86	4.55
	RareSp	AMH10+ TA1+ TL1	0.03	0.07	2.39	5.94
	RiffDwell	AMH10+ LDH13+ LDL6+ TL1	0.03	0.05	0.75	1.34
	SpecInsect	AMH10+ ML20+ TL1	0.31	0.61	12.95	18.89
	TopPred	TA1+ TL1	0.06	0.10	1.72	2.97
IP	AllSp	AMH10+ TL1	0.07	0.10	0.15	0.22
	HWIntol	AMH10+ TA1+ TL1	0.06	0.16	1.18	3.04
	Intolerants	TA1+ TL1	0.03	0.04	0.41	0.59
	Invert	AMH10+ TA1+ TL1	0.03	0.06	0.18	0.34
	LithSpawn	AMH10+ TA1	0.66	1.34	7.12	13.00
	Natives	AMH10+ LRA7+ FH6+TL1	0.23	0.42	0.58	1.06
	PoolDwell	AMH10+ TL1	0.15	0.30	0.63	1.18
	RiffDwell	TA1	0.10	0.21	1.94	3.95
	SpecInsect	TA1+ FH6	0.15	0.29	0.95	1.82
	TopPred	AMH10+ FH6	0.01	0.02	0.30	0.49
		Overall mean	0.17	0.33	2.57	4.96

[1] Mean values were calculated using the site-specific data within the "Richness_CR.txt" and "Richness_POF.txt" files from [3]. Means were calculated only among sites that exhibited some decline in richness among all withdrawal scenarios relative to richness predicted under 0 withdrawals. Blank cells indicate fish groups where no sites resulted in a decline in species richness among withdrawal scenarios.

Table S4. Median values of predicted ecological withdrawal thresholds under constant-rate and percent-of-flow withdrawal scenarios for each fish group, and overall means of median thresholds calculated for each ecoregion. n = number (sum) of sites that reached an ecological withdrawal threshold for each fish group. Cumulative n[1] = sum of threshold sites (n) across fish groups for each ecoregion.

Ecoregion	Fish group	Streamflow characteristics	Constant-rate ecological withdrawal threshold (m³/s)[1]								Percent-of-flow ecological withdrawal threshold (%)[1]							
			MFL0		MFL5		MFL10		MFL30		MFL0		MFL5		MFL10		MFL30	
			n	Median	n	Median	n	Median	n	Median	n	Median	n	Median	n	Median	n	Median
BR	AllSp	AMH10	2	0.64	2	0.65	2	0.67	2	0.74	2	23.5	2	23.5	2	23.5	2	25.0
	Invert	AMH10	2	0.69	2	0.71	2	0.72	2	0.79	2	27.0	2	27.0	2	27.0	2	28.0
	LithSpawn	AMH10	2	0.68	2	0.69	2	0.72	2	0.78	2	26.0	2	26.0	2	26.0	2	27.5
		Mean of medians		0.67		0.68		0.70		0.77		25.5		25.5		25.5		26.8
		Cumulative n[2]	6		6		6		6		6		6		6		6	
RV	AllSp	FL2	5	0.79	10	0.59	13	0.43	6	0.23	0		0		3	30.0	6	16.0
	Intolerants	LDH16	2	0.69	2	0.68	2	0.64	2	0.52	0		0		0		0	
	Invert	MA41	13	0.31	12	0.27	12	0.28	11	0.40	12	6.5	12	6.5	12	6.5	11	6.0
	LithSpawn	FL2	4	0.71	10	0.59	12	0.45	6	0.23	0		0		2	32.5	6	16.0
	Natives	FL2	5	0.79	10	0.59	13	0.43	7	0.26	0		0		3	30.0	7	15.0
	Omni	FL2	3	0.62	10	0.59	12	0.45	6	0.23	0		0		1	30.0	6	16.0
	PoolDwell	FL2	4	0.81	9	0.54	12	0.35	6	0.28	0		0		3	30.0	6	16.0
	SpecInsect	LDH16+ TA1	11	0.20	10	0.24	4	0.06	8	0.57	5	6.0	4	14.5	1	1.0	7	6.0
		Mean of medians		0.62		0.51		0.39		0.34		6.3		10.5		22.9		13.0
		Cumulative n[2]	47		73		80		52		17		16		25		49	
CP	AllSp	TL1	10	0.09	1	0.03	0		0		0		1	28.0	0		0	
	HWIntol	AMH10+ LDH13+ LDL6+ TL1	10	0.01	6	0.68	4	0.34	2	0.27	4	8.5	6	25.5	4	8.5	3	2.0
	Intolerants	AMH10+ ML20+ TL1	10	0.09	7	0.54	6	0.38	5	0.31	7	8.0	7	8.0	6	8.0	5	9.0
	Invert	AMH10	2	0.92	2	1.01	1	0.71	1	0.74	1	13.0	1	13.0	1	13.0	1	14.0
	LithSpawn	AMH10+ TA1+ TL1	9	0.09	1	0.03	3	0.31	0		5	7.0	3	14.0	3	17.0	1	7.0
	Natives	TL1	10	0.09	1	0.03	0		0		0		1	28.0	0		0	
	PoolDwell	TA1+ TL1	9	0.09	1	0.03	2	0.30	0		5	13.0	3	21.0	1	29.0	0	
	RareSp	TA1+ TL1	9	0.09	2	0.05	2	0.07	0		4	9.5	2	9.0	2	18.0	1	5.0
	RiffDwell	AMH10+ TL1	10	0.09	1	0.03	1	0.79	1	0.85	1	16.0	1	16.0	1	16.0	1	17.0
	SpecInsect	AMH10+ TA1+ TL1	9	0.09	2	0.05	3	0.11	1	0.03	5	6.0	3	6.0	3	10.0	1	2.0
	TopPred	MA41+ TL1	10	0.11	1	0.03	1	0.14	1	0.20	1	4.0	1	4.0	1	4.0	1	5.0
		Mean of medians		0.16		0.23		0.35		0.40		9.4		15.7		13.7		7.6
		Cumulative n[2]	98		25		23		11		33		29		22		14	
IP	AllSp	AMH10+ TL1	30	0.24	24	0.26	14	0.18	0		0		12	31.0	12	27.5	0	
	HWIntol	FH6+ TA1	26	0.23	8	0.10	8	0.27	8	0.28	11	12.0	6	14.5	3	5.0	7	5.0
	Intolerants	AMH10+ FH6	9	0.37	9	0.37	9	0.37	7	0.23	2	18.5	2	18.5	2	18.5	3	13.0
	Invert	AMH10+ LRA7+ FH6+TL1	29	0.23	32	0.26	27	0.45	5	0.17	0		11	31.0	12	33.5	0	
	LithSpawn	TA1	27	0.17	8	0.01	6	0.08	5	0.20	10	3.5	8	9.0	3	2.0	6	1.0
	Natives	AMH10+ TA1+ TL1	30	0.23	24	0.26	11	0.17	1	1.33	9	31.0	14	29.0	9	21.0	0	
	PoolDwell	AMH10+ TA1+ TL1	30	0.21	25	0.26	11	0.17	1	1.19	10	30.5	14	26.5	9	21.0	1	37.0
	RiffDwell	TA1+ TL1	29	0.20	26	0.20	14	0.17	3	0.99	10	13.5	16	24.5	11	21.0	3	7.0
	SpecInsect	AMH10+ TA1	27	0.26	4	0.01	2	0.53	2	0.92	10	20.0	4	15.5	1	15.0	2	19.0
	TopPred	AMH10+ TL1	30	0.21	27	0.31	16	0.17	1	0.74	1	21.0	15	26.0	14	21.5	1	21.0
		Mean of medians		0.23		0.20		0.26		0.67		18.8		22.6		18.6		14.7
		Cumulative n[2]	267		187		118		33		63		102		76		23	

[1] Median values were calculated using the site-specific data within the "Thresholds_CR.txt" and "Thresholds_POF.txt" files from [3].

[2] Sites that reached a threshold in multiple fish groups were counted more than once, meaning cumulative n can be greater than the number of individual stream sites for each ecoregion.
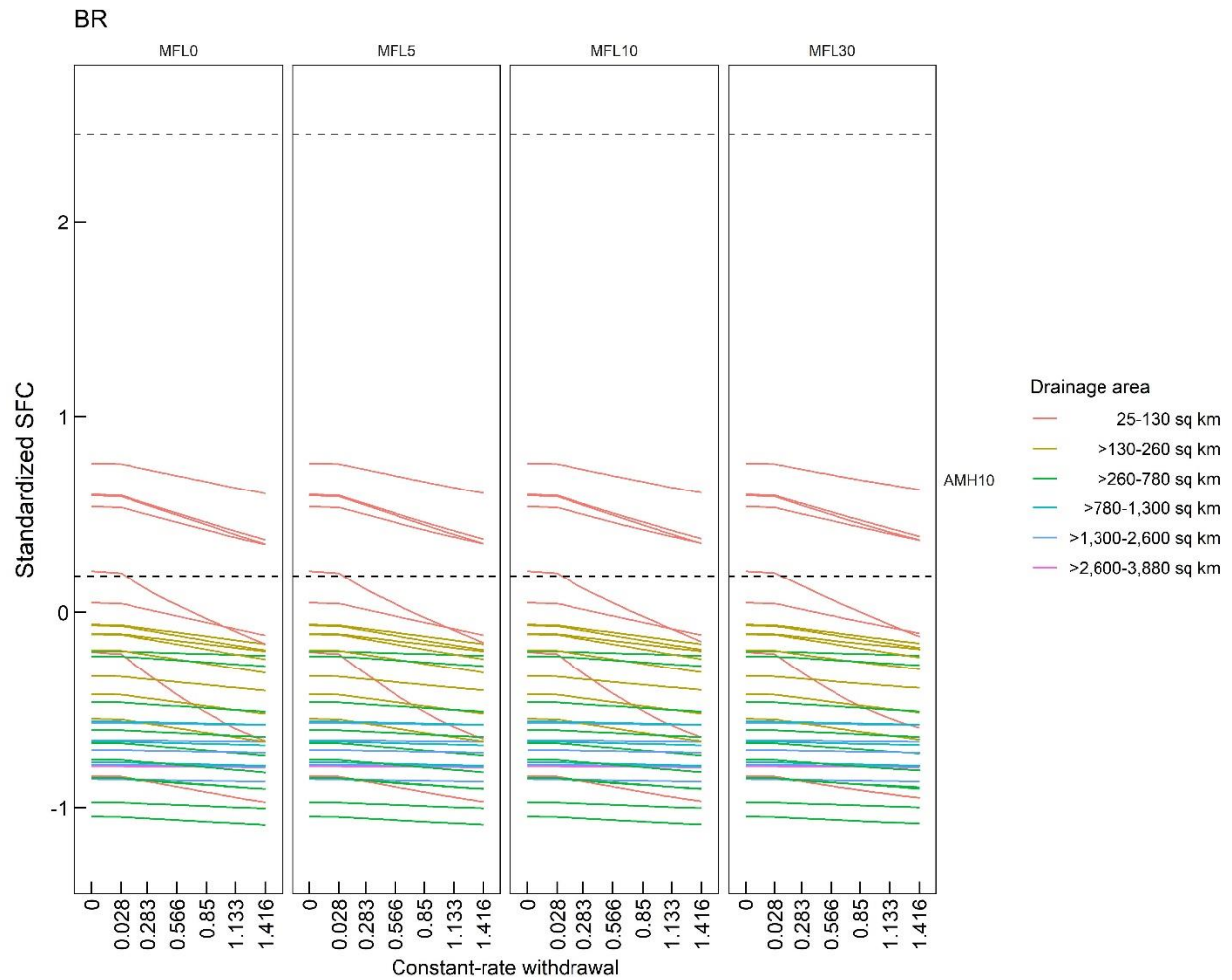
Figure S1. Responses of SFCs among Blue Ridge (BR) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion[1–4].
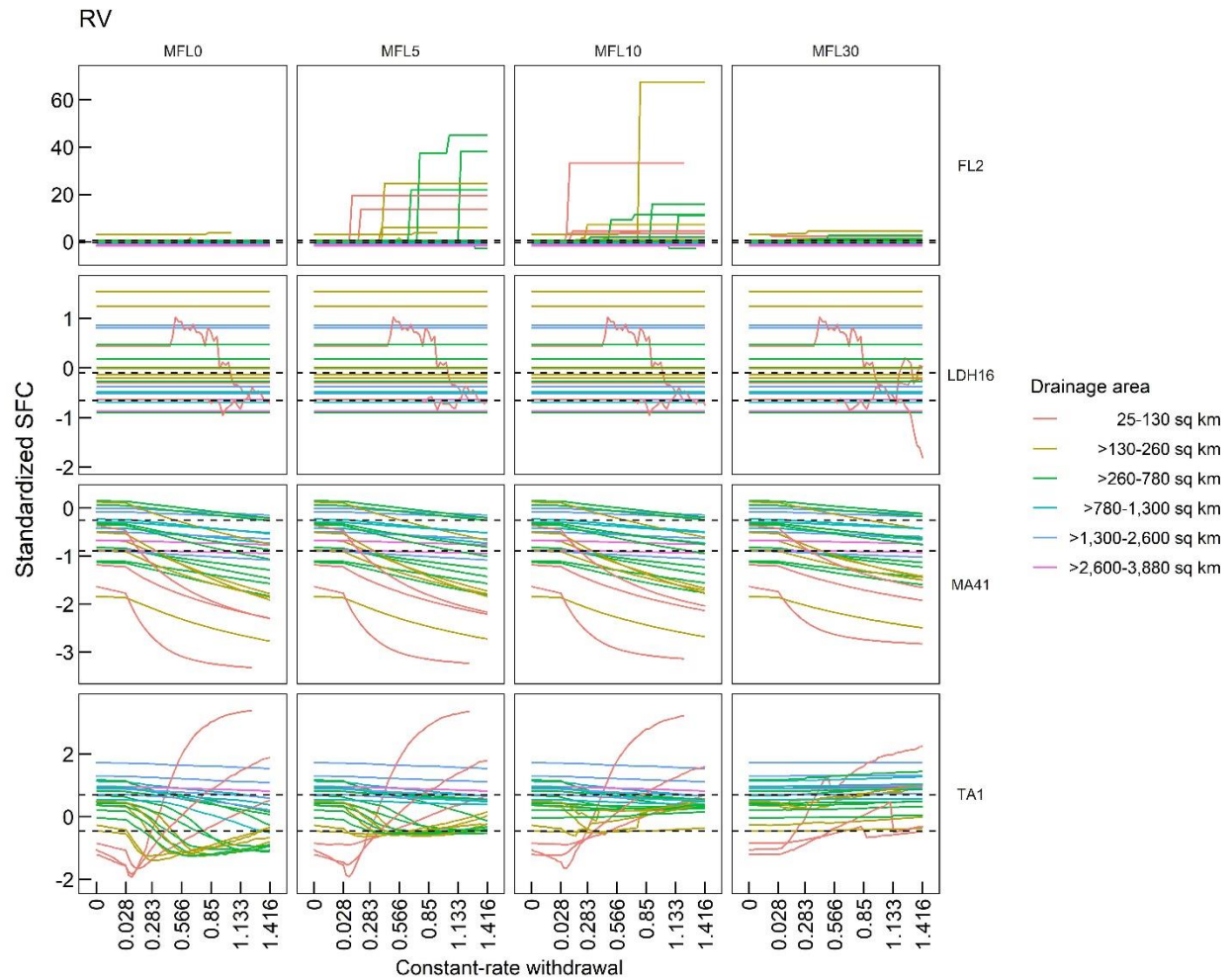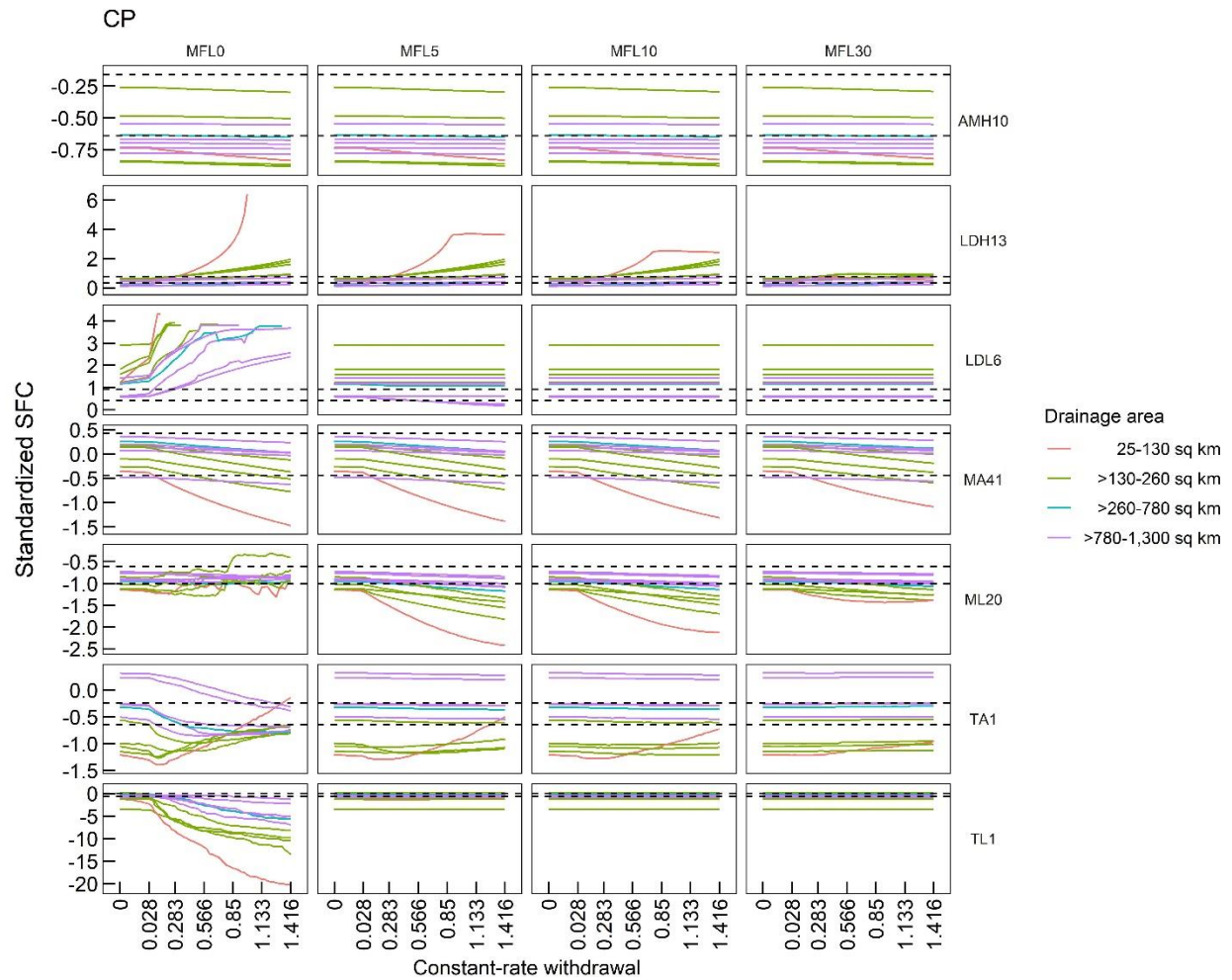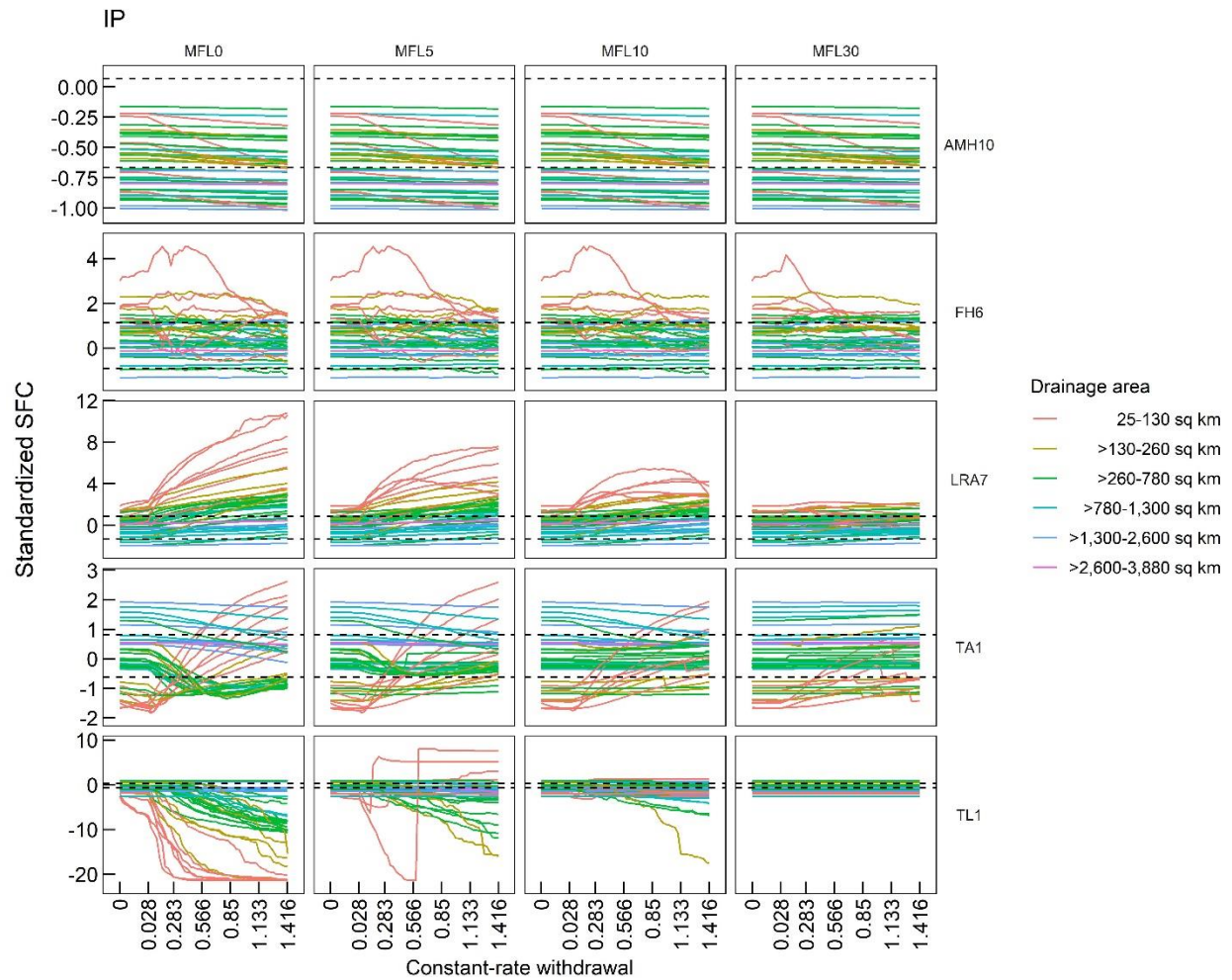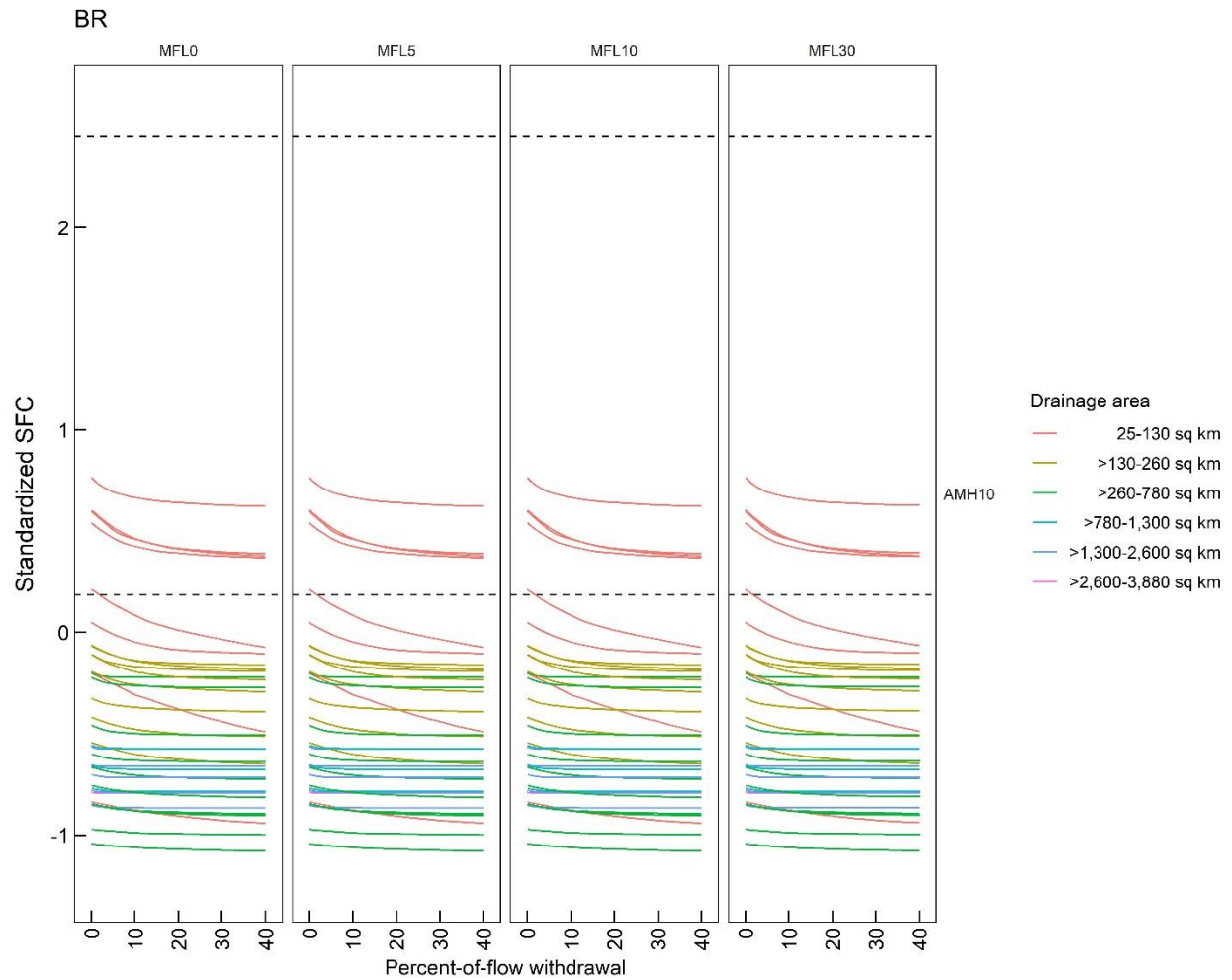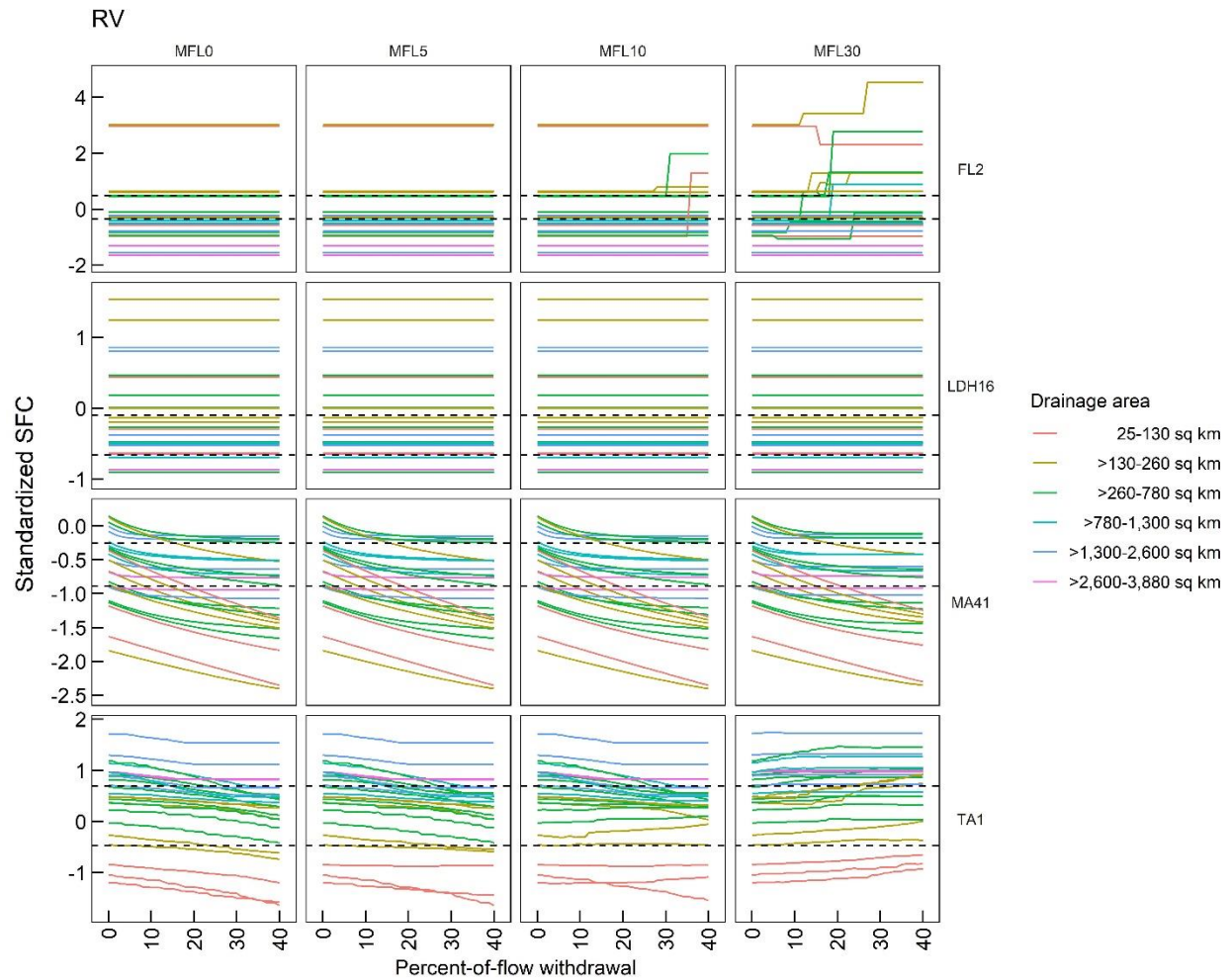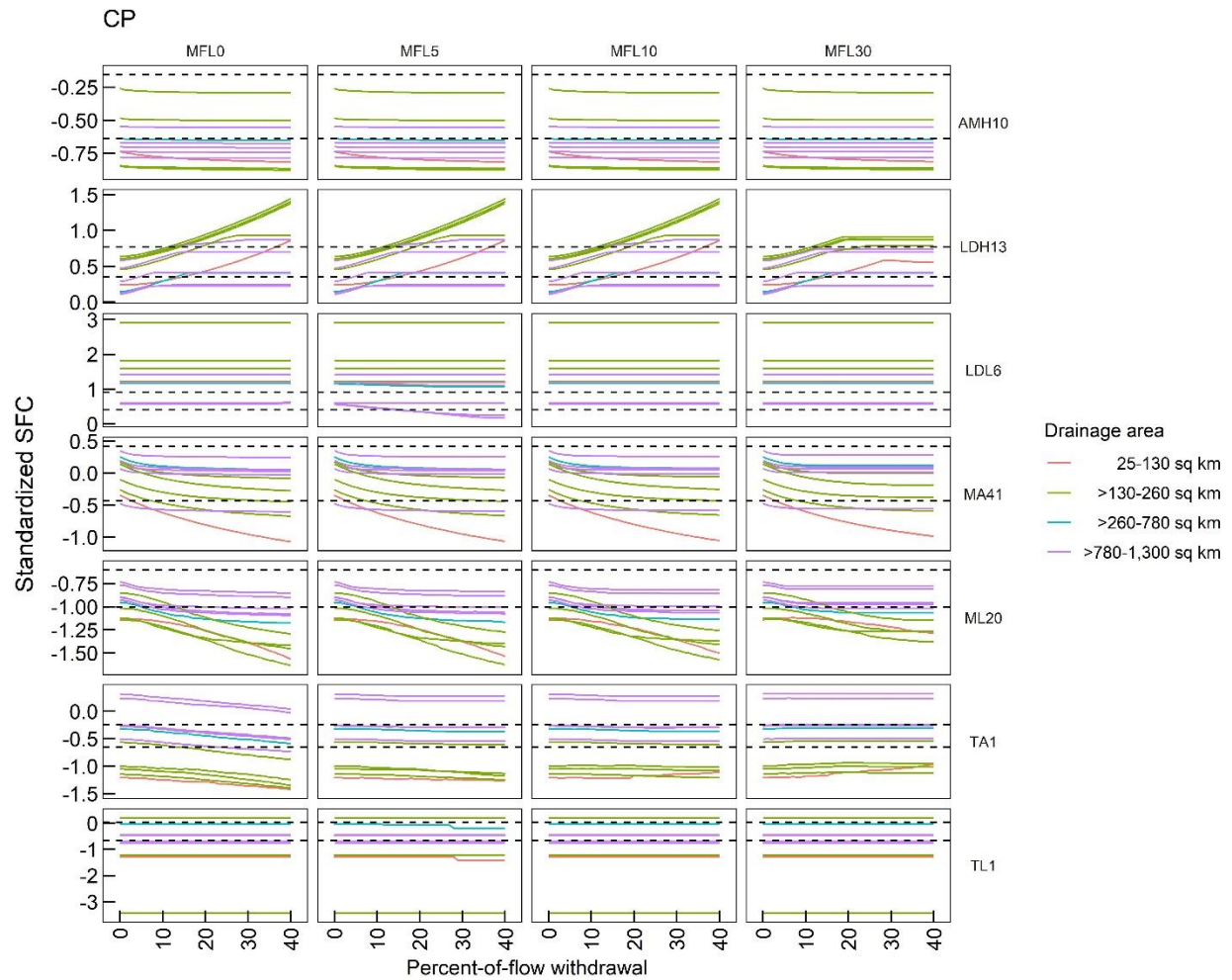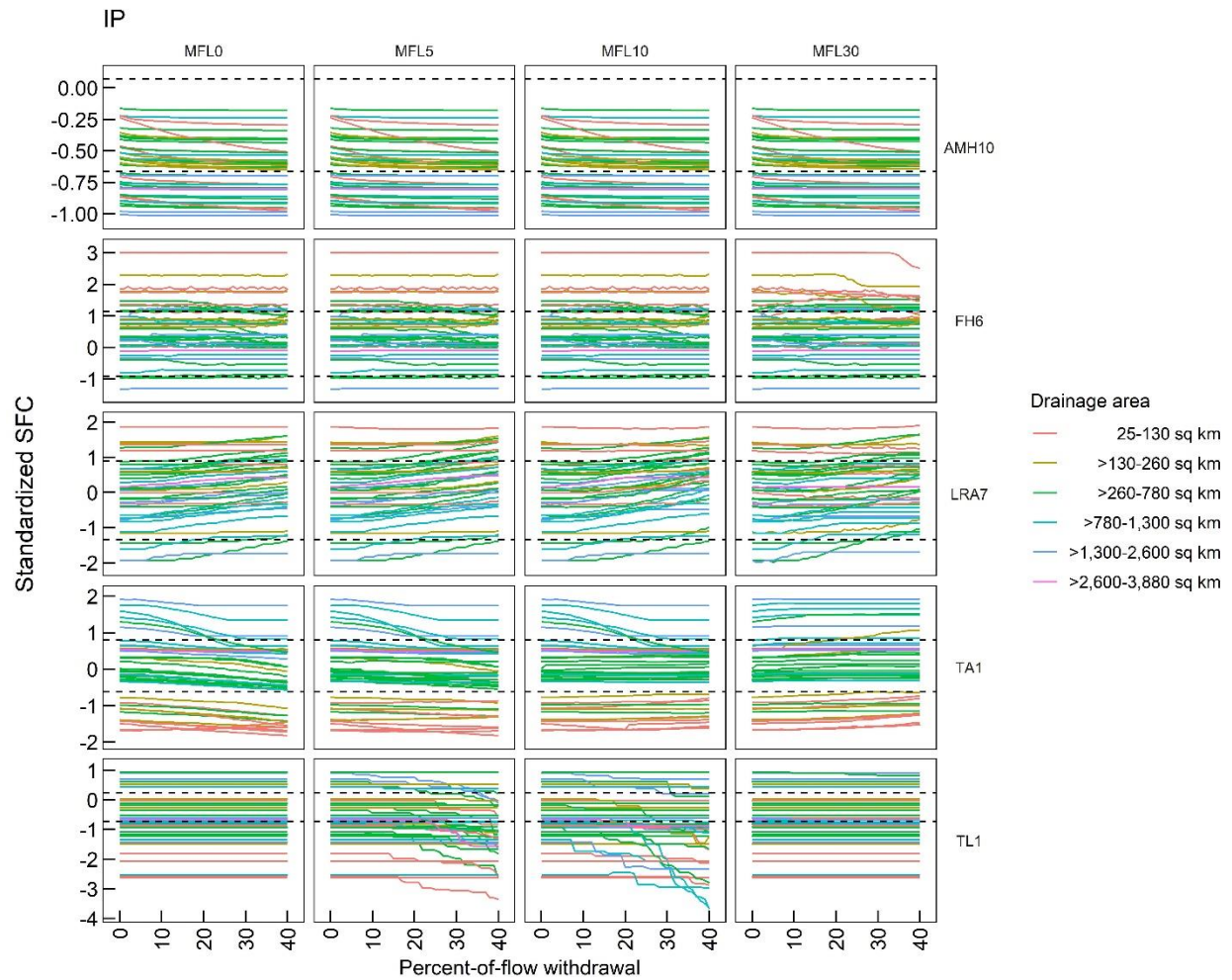
Figure S2. Responses of relevant SFCs among Ridge and Valley (RV) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].
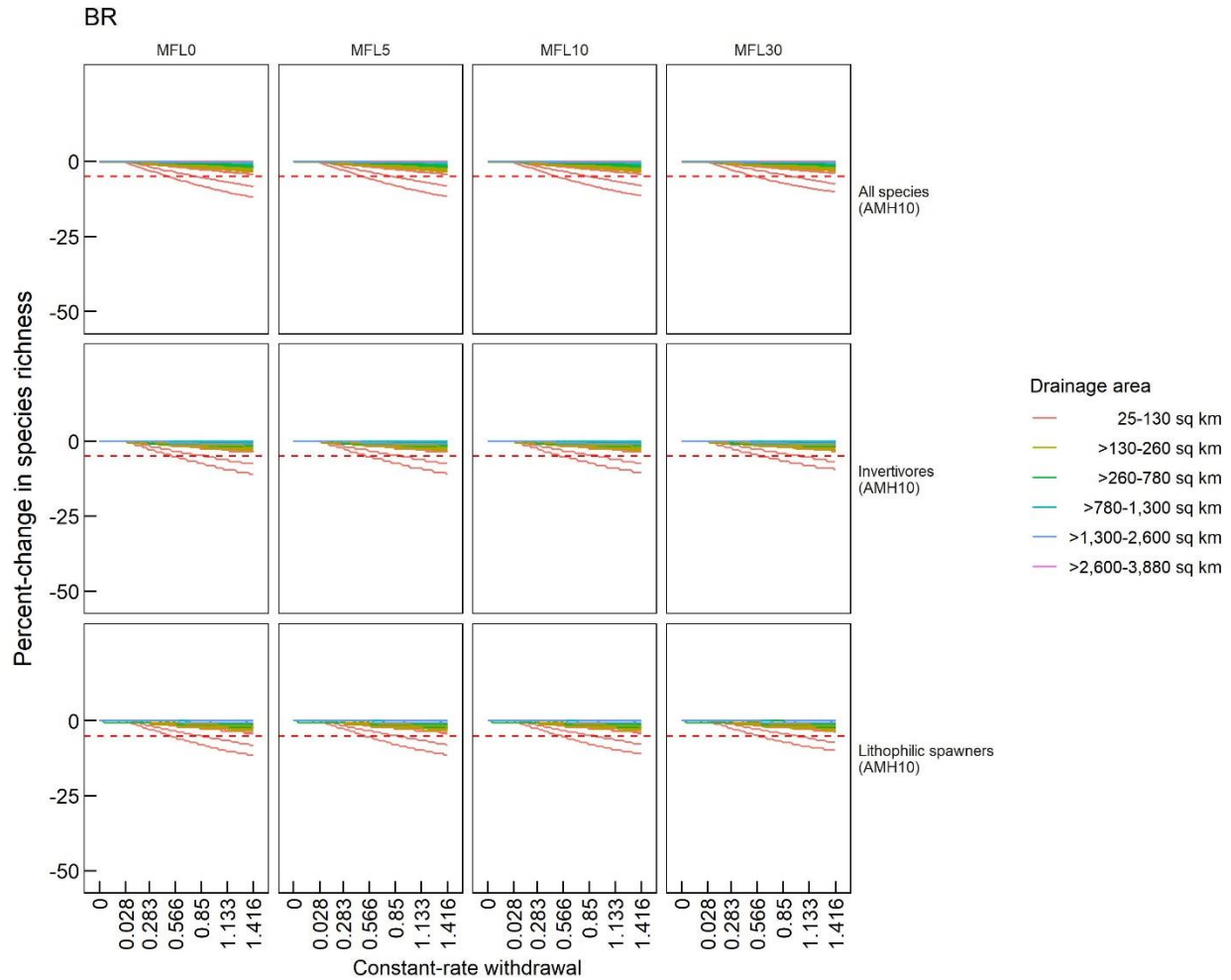
Figure S3. Responses of relevant SFCs among Cumberland Plateau (CP) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].

Figure S4. Responses of relevant SFCs among Interior Plateau (IP) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].

Figure S5. Responses of relevant SFCs among Blue Ridge (BR) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].

Figure S6. Responses of relevant SFCs among Ridge and Valley (RV) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].

Figure S7. Responses of relevant SFCs among Cumberland Plateau (CP) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].

Figure S8. Responses of relevant SFCs among Interior Plateau (IP) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent individual stream sites; horizontal dashed lines represent the interquartile range (IQR) of SFCs from reference sites within the ecoregion [1–4].
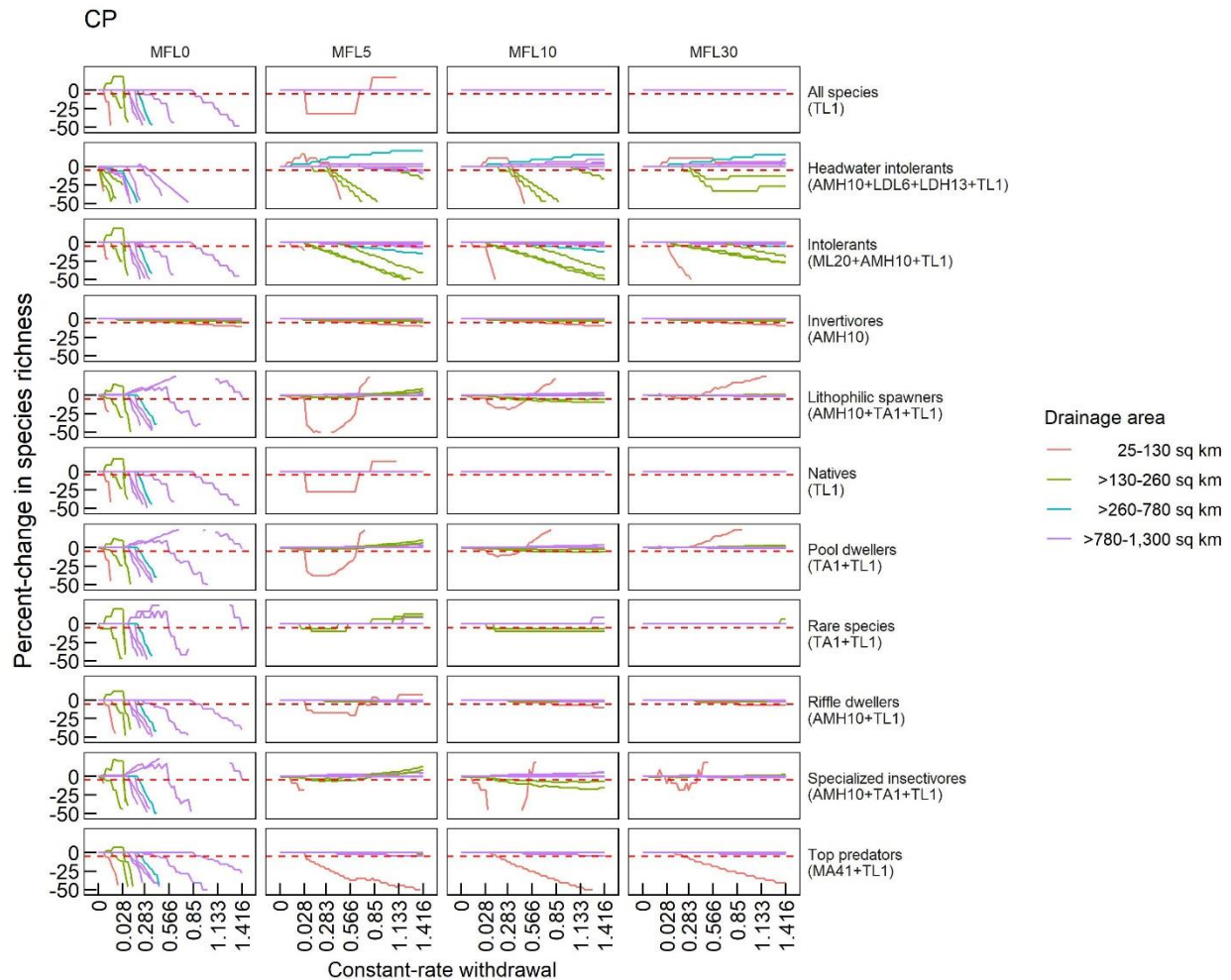
Figure S9. Predicted percent-change (%) in fish species richness among Blue Ridge (BR) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario-specific responses are reported in [3].
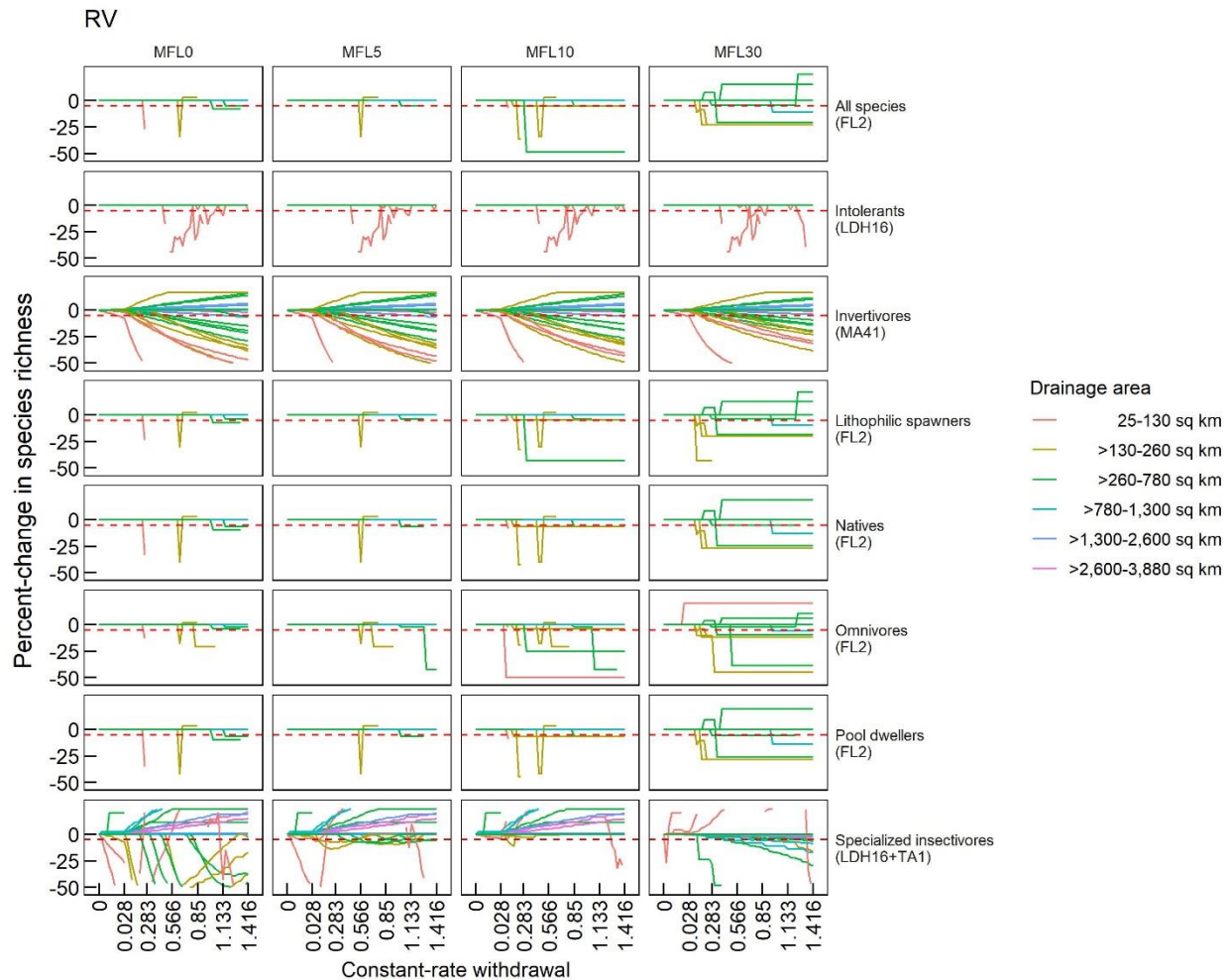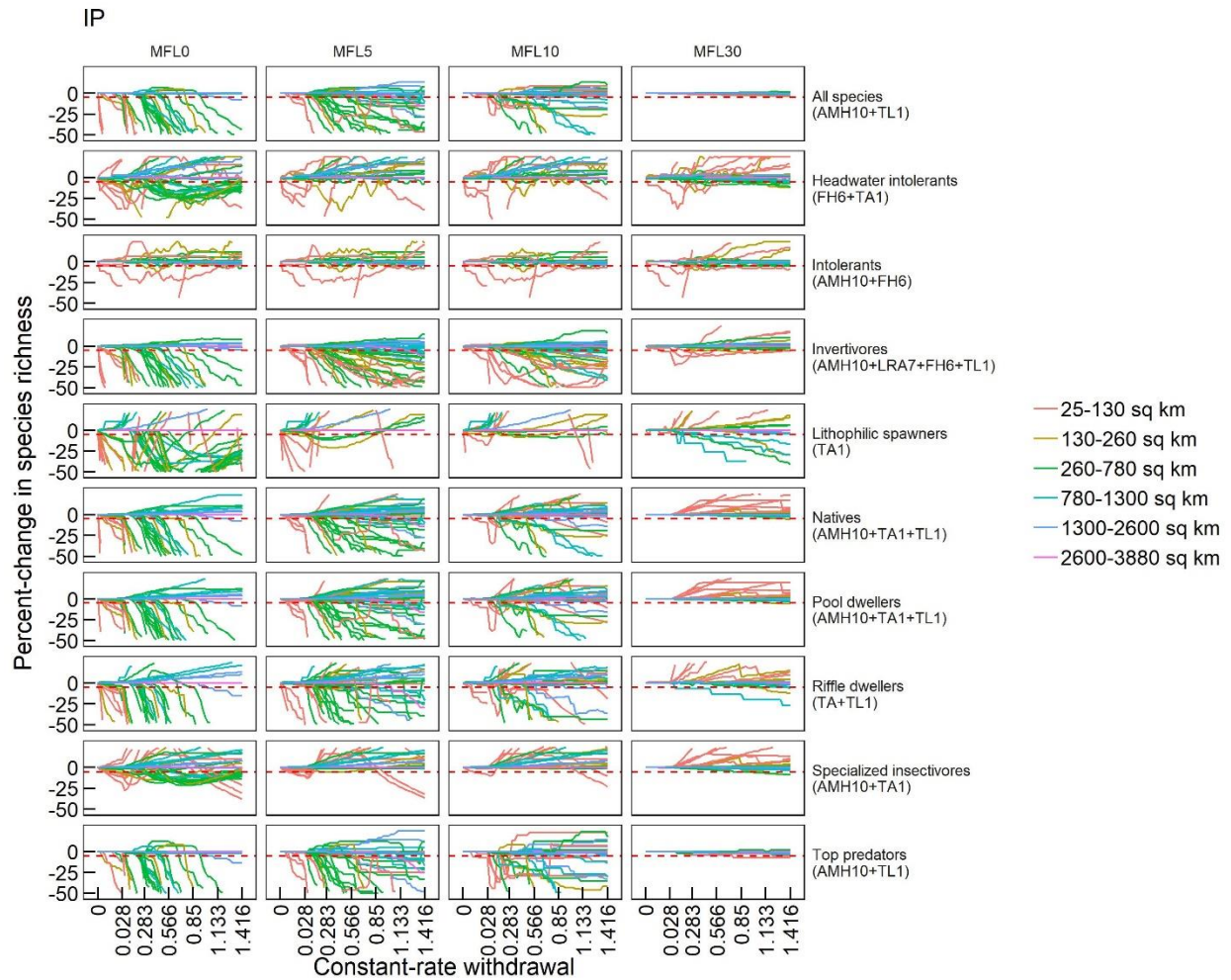
Figure S10. Predicted percent (%) change in fish species richness among Ridge and Valley (RV) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].
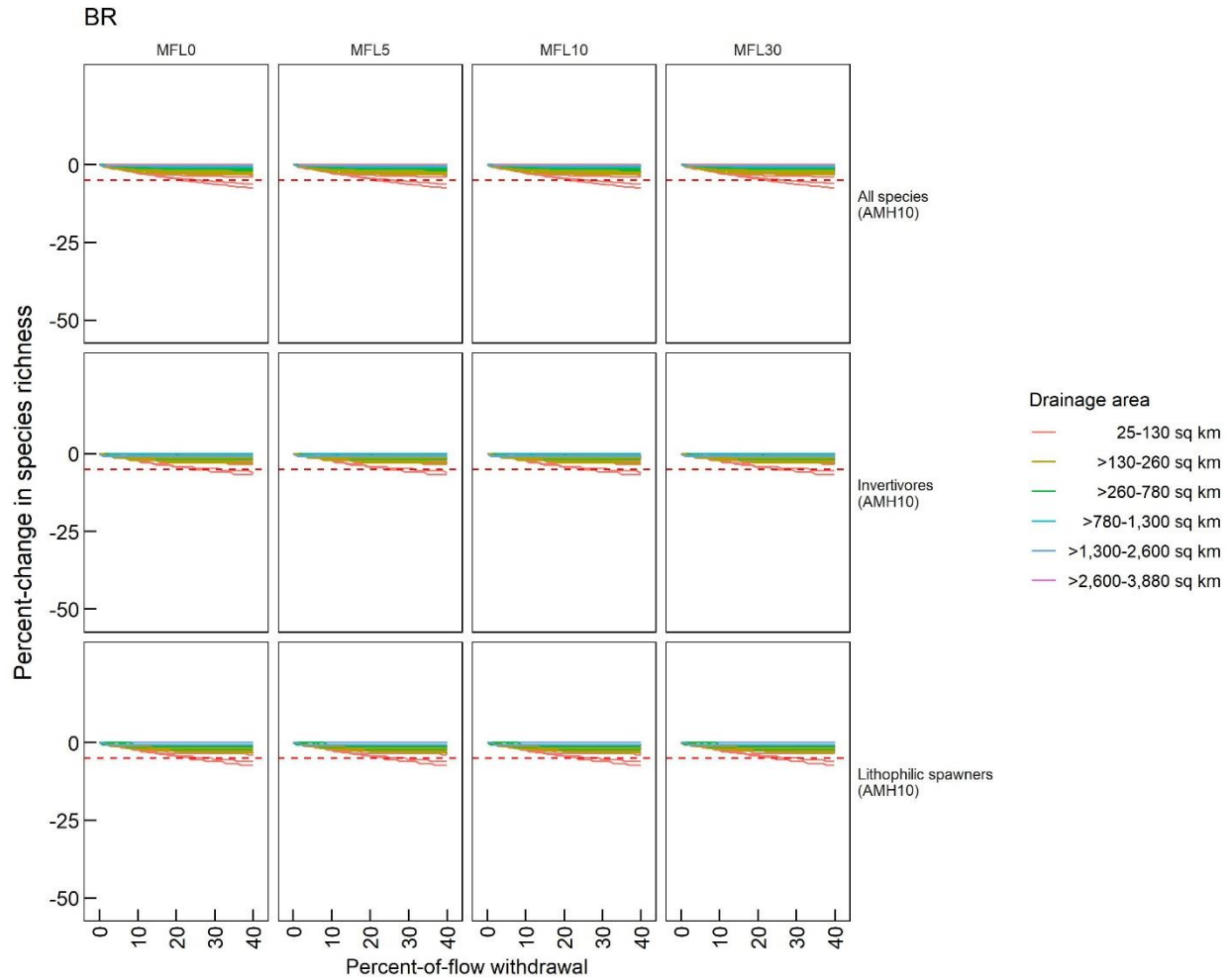
Figure S11. Predicted percent (%) change in fish species richness among Cumberland Plateau (CP) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].

Figure S12. Predicted percent (%) change in fish species richness among Interior Plateau (IP) streams to incremental constant-rate withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].
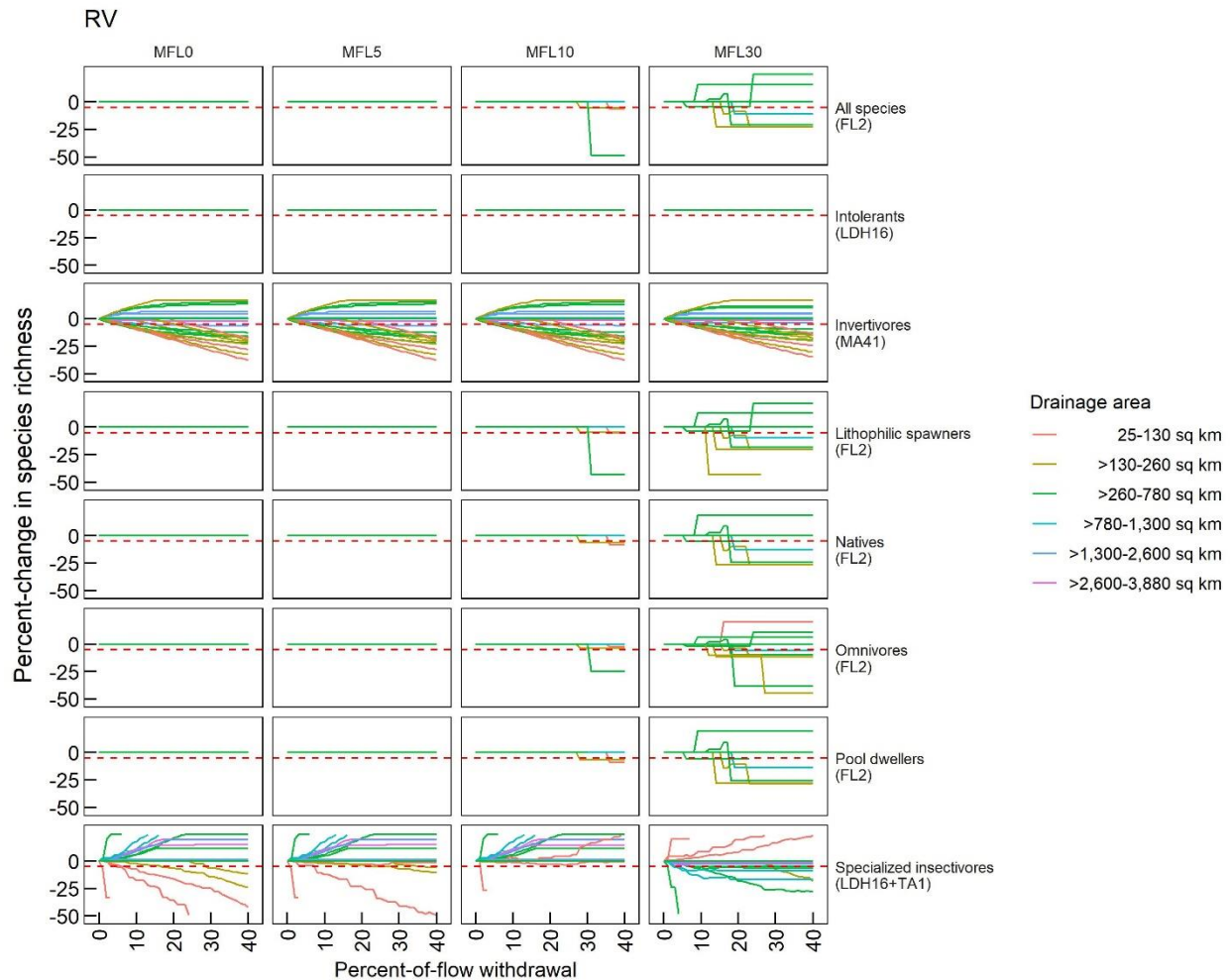
Figure S13. Predicted percent (%) change in fish species richness among Blue Ridge (BR) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].
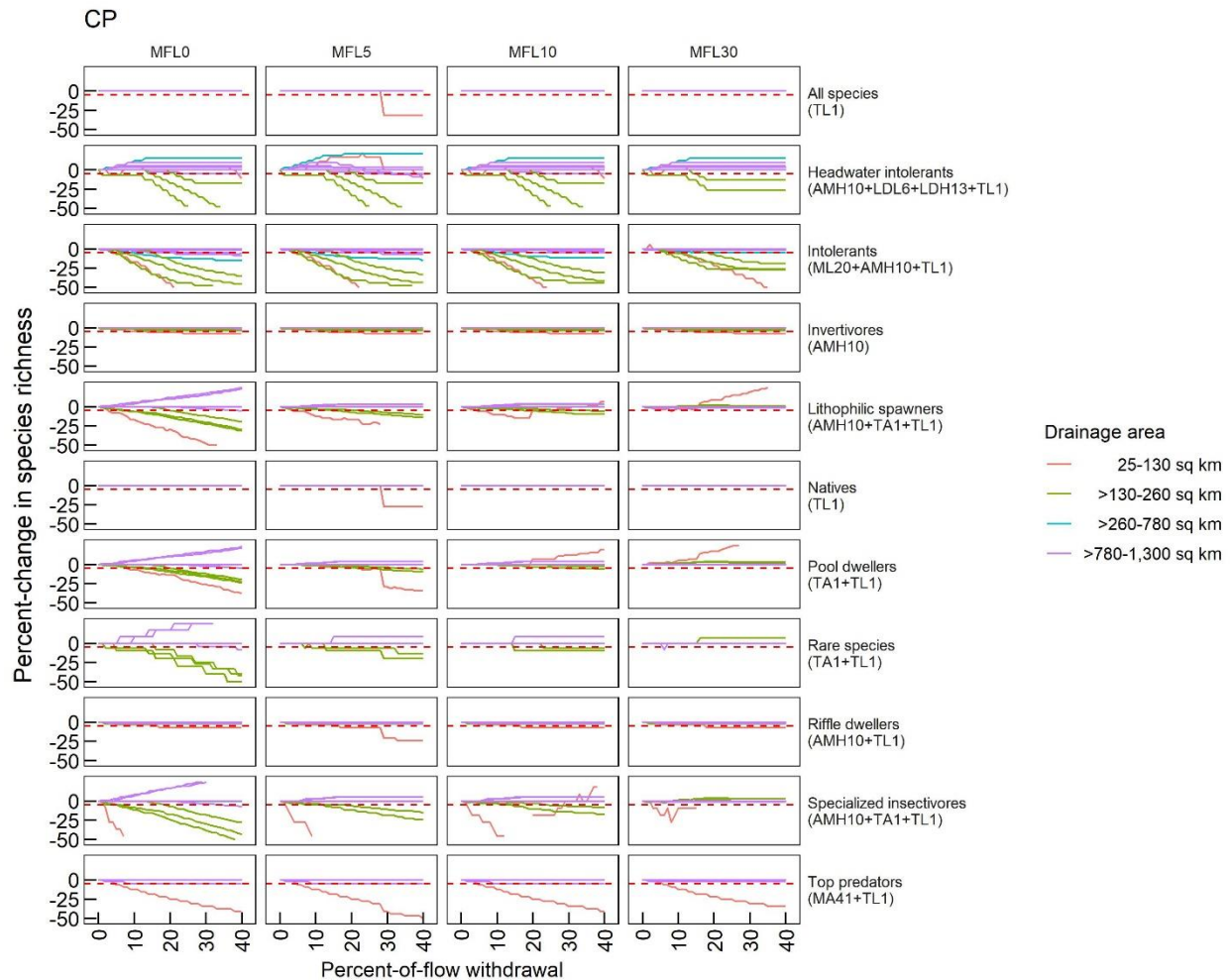
Figure S14. Predicted percent (%) change in fish species richness among Ridge and Valley (RV) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].
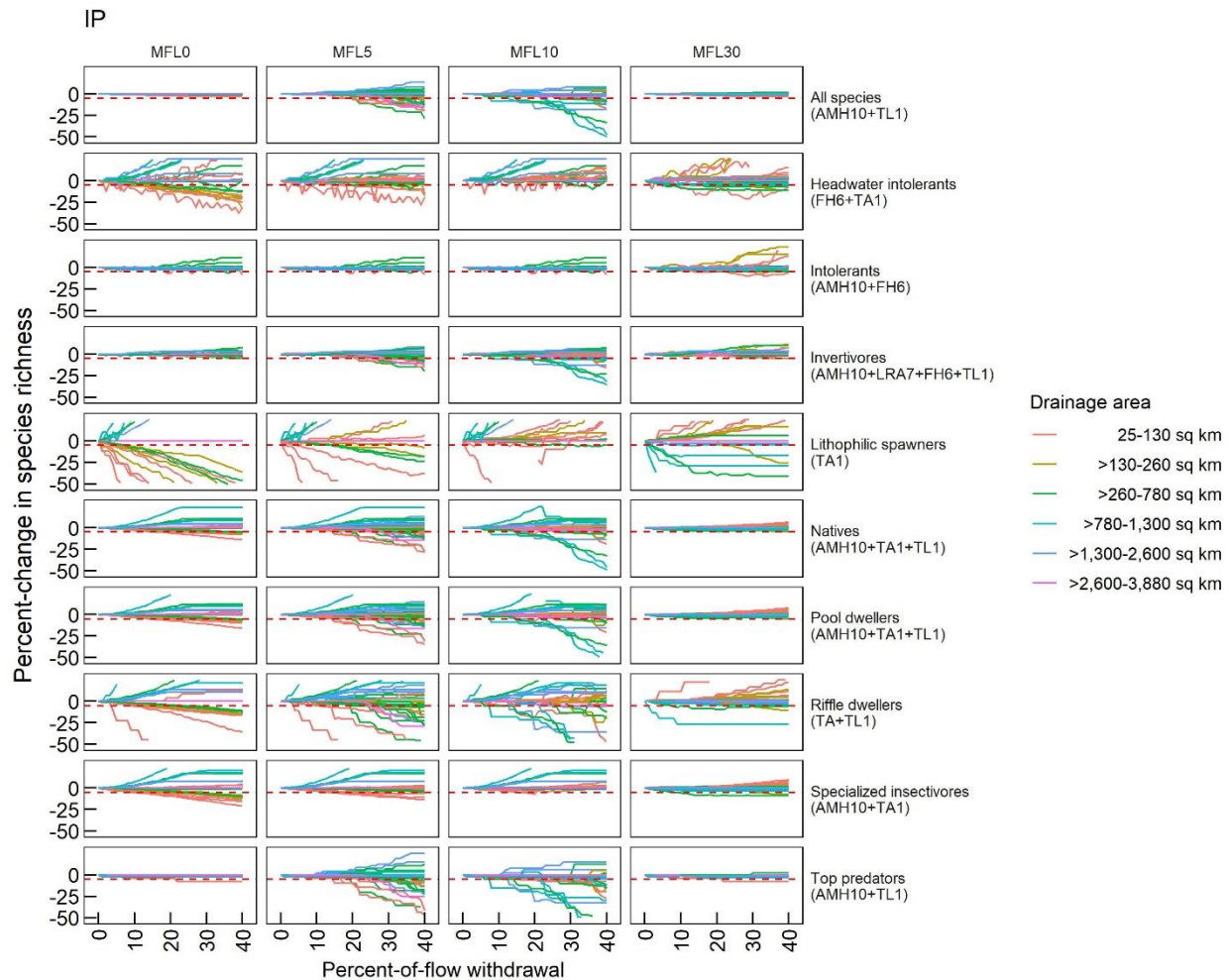
Figure S15. Predicted percent (%) change in fish species richness among Cumberland Plateau (CP) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].

Figure S16. Predicted percent (%) change in fish species richness among Interior Plateau (IP) streams to incremental percent-of-flow withdrawals and minimum flow levels (MFL). Solid lines represent change in richness at individual stream sites; horizontal dashed line indicates -5% change (loss) in predicted species richness. Maximum allowable withdrawal (MAW) thresholds occur at the intersections of solid and dashed lines. SFC(s) associated with the ecological limit function for each fish group and ecoregion are in parentheses. Site-specific and withdrawal scenario specific responses are reported in [3].
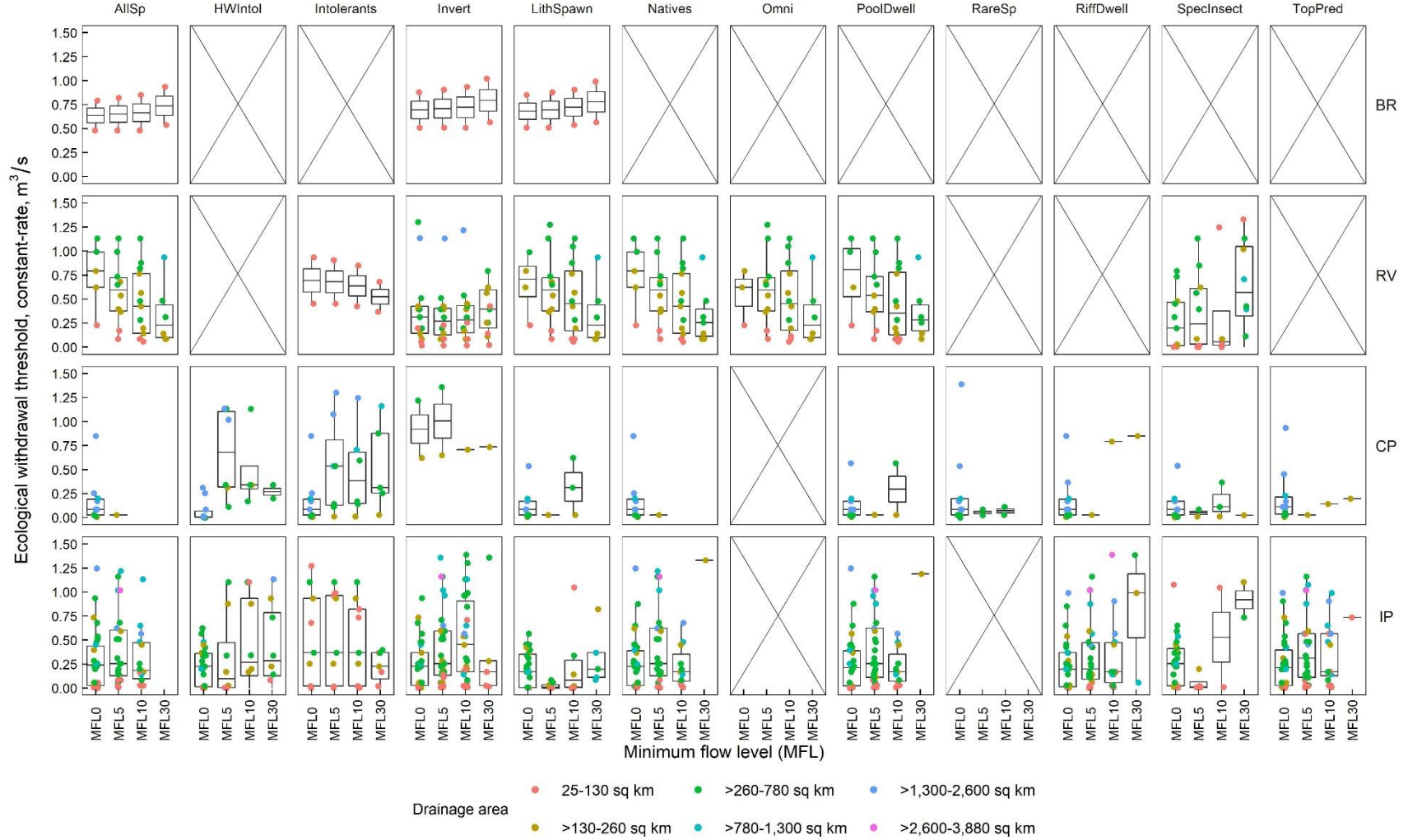
Figure S17. Boxplots of predicted ecological withdrawal thresholds under constant-rate (CR) withdrawal scenarios summarized by fish group and MFL for each ecoregion. Points are threshold values for individual stream sites and are color coded by stream drainage area size. Boxes with "X" indicate fish groups with no ecological limit function. Site-specific and withdrawal scenario specific responses are reported in [3]
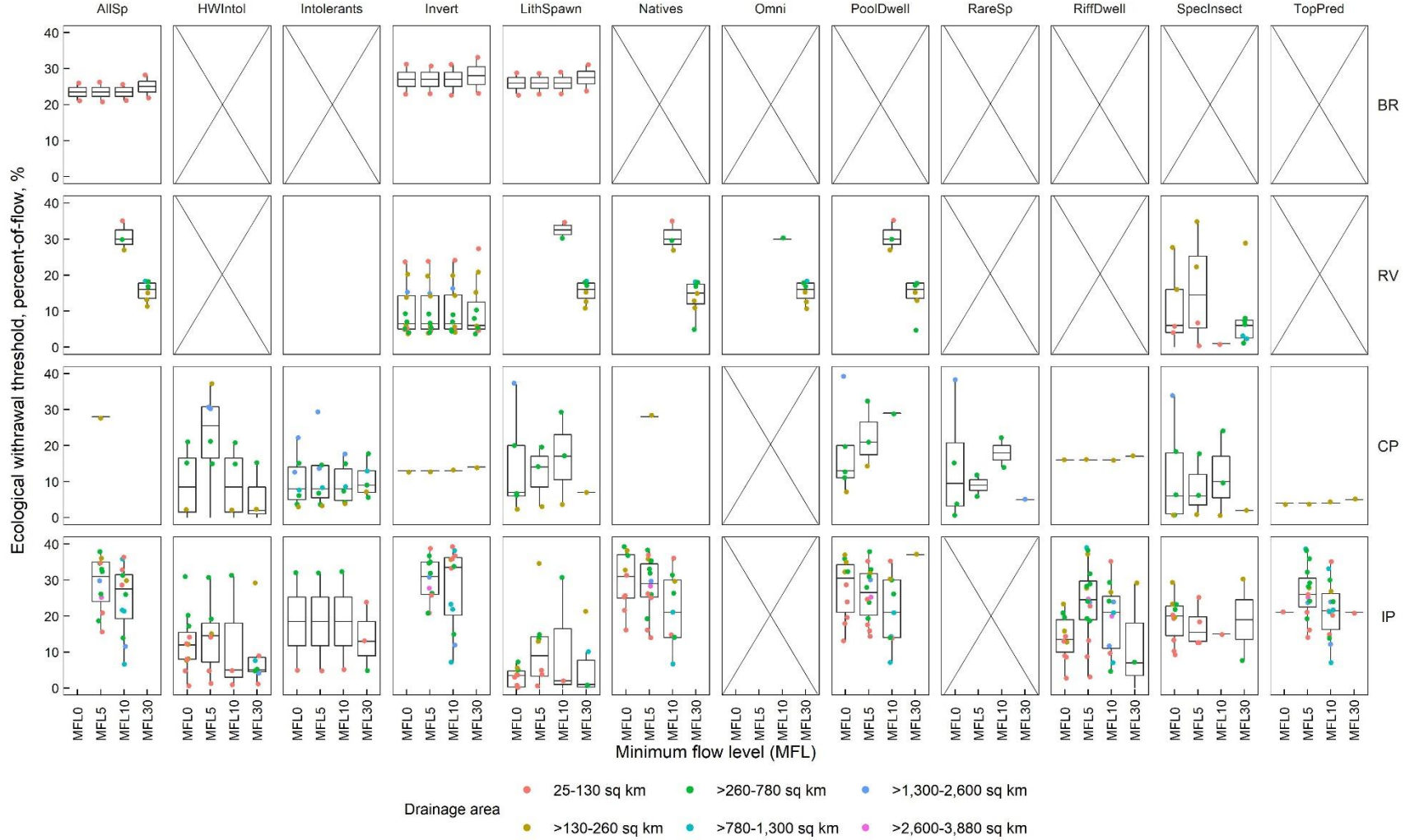
Figure S18. Boxplots predicted ecological withdrawal thresholds under percent-of-flow (POF) withdrawals scenarios summarized by fish group and MFL for each ecoregion. Points are threshold values for individual stream sites and are color coded by stream drainage area size. Boxes with "X" indicate fish groups with no ecological limit function.. Site-specific and withdrawal scenario specific responses are reported in [3].

References

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