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Remote land use impacts on river flows through atmospheric teleconnections

Lan Wang-Erlandsson et al.

Correspondence to: Lan Wang-Erlandsson (lan.wang@su.se)

Supplementary Information

Table S1. Methods for estimating land-use change impacts on rainfall or river flows.

Method	Key merits	Key limitations*	References
Earth System Model (ESM)	- Inclusion of multiple land-atmosphere-ocean feedbacks - Water balance closure	- Computationally costly. - Does not always include irrigation.	(Betts et al., 2015; Garcia et al., 2016)
General circulation model (GCM)	- Inclusion of multiple land-atmosphere-ocean feedbacks. (Sea surface temperature can be fixed to increase the signal-to-noise ratio.) - Coupled models close the water balance.	- Considerable noise in precipitation and runoff change (i.e., few grid cells passing significance test). - Does not always include irrigation. - Difficult to understand mechanisms. - Computationally costly.	(Bring et al., 2015; Findell et al., 2007; Pitman et al., 2009)
Regional climate model (RCM)	- Simulation of changes in convection and orographic precipitation - Can simulate enhanced local rainfall from deforested patches - Higher signal-to-noise ratio for precipitation change due to fixed boundary conditions	- Limitations in representing clouds - Potentially ignores water balance closure - No feedback across fixed regional boundaries	(Bagley et al., 2014; Lawrence and Vandecar, 2014)
Offline land surface model (LSM)	- Often includes irrigation.	- No land-atmosphere feedback. - No water balance closure.	(Gerten et al., 2008; Rost et al., 2008a, 2008b; Sterling et al., 2012)
Observations	- Observed	- Correlation rather than causation, thus, often combined with modelling. - Challenging attribution due to concurrent climate change and LUC	(Spracklen et al., 2012)
Meta-analysis	- Synthesis results from many different types of studies	- Limitation in spatially and temporally resolved estimates	(Spracklen and Garcia-Carreras, 2015)
Two-way coupled moisture recycling	- Includes irrigation - Phenology (LAI) responds to precipitation change - Water balance closure - Computationally efficient	- Ignoring other types of land-atmosphere feedback.	This study, (Keys et al., 2016)

*Limitations of most models in simulating vegetation feedback (e.g., rooting depth adjustment), disturbance processes (e.g., pathogens), and societal response (e.g., behavioural change) (Reyer et al., 2015).

Table S2. Land-cover and land-use parameterisation in STEAM.

	Group	LAI_{max}	LAI_{min}	α	h_{max}	h_{min}	z_{0g}	$r_{st,min}$
Unit		-	-	-	m	m	m	s m^{-1}
01: Water (Wa)	I – W	0	0	0.08	0	0	0.00137	0
02: Tropical evergreen forest/woodland (TrE)	II – F	5.5	5	0.20	30	30	0.02	200
03: Tropical deciduous forest/woodland (TrD)	II – F	5.5	1	0.18	30	30	0.02	200
04: Temp. broadleaf evergreen forest/woodland (TeB)	II – F	5.5	2	0.18	25	25	0.02	200
05: Temp. needleleaf evergreen forest/woodland (TeN)	II – F	5.5	2	0.15	17	17	0.02	300
06: Temp. deciduous forest/Woodland (TeD)	II – F	5.5	0.5	0.18	25	25	0.02	200
07: Boreal evergreen forest/Woodland (BoE)	II – F	5.5	2	0.15	17	17	0.02	300
08: Boreal deciduous forest/Woodland (BoD)	II – F	5.5	0.5	0.18	25	25	0.02	200
09: Evergreen/Deciduous Mixed Forest/Woodland (Mix)	II – F	5	1	0.17	20	20	0.02	250
10: Savanna (Sav)	III – S	2	0.5	0.25	0.8	0.1	0.02	150
11: Grassland/Steppe (Gra)	III – S	2	0.5	0.25	0.8	0.05	0.01	110
12: Dense Shrubland (DShr)	III – S	2.5	1	0.2	1.5	1.5	0.02	200
13: Open shrubland (OShr)	III – S	1.5	0.5	0.15	1	1	0.02	200
14:Tundra (Tun)	IV – B	2	1	0.15	0.8	0.1	0.01	80
15 Desert (Des)	IV – B	0.1	0	0.25	0.4	0	0.001	200
16 Polar desert/rock/ice (Ice)	IV – B	0	0	0.70	0	0	0.001	0
17: Wetland (Wet)	V – O	4	1	0.15	1	0.05	0.01	150
18: Urban (Urb)	IV – B	1	0.1	0.18	0.8	0	0.001	250
19: Pasture (Pas)	III – S	2	0.5	0.22	0.8	0.05	0.01	150
20: Rainfed cropland (RfCro)	VI – C	3.5	0.5	0.22	0.8	0.05	0.005	150
21: irrigated crop (IrCro)	VII – I	3.5	3.5	0.22	0.8	0.8	0.005	150
22: Irrigated rice (IrRic)	VIII - R	3.5	3.5	0.22	0.8	0.8	0.005	150

LAI_{max} is the maximum leaf area index, LAI_{min} is the minimum leaf area index, α is the albedo, h_{max} is the maximum plant height, h_{min} is the minimum plant height, z_{0g} is the ground roughness, and $r_{st,min}$ is the minimum stomatal resistance.

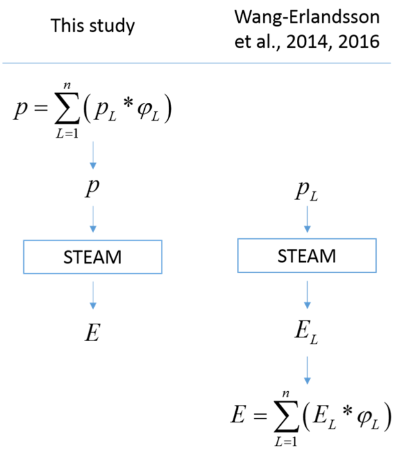

Figure S1. Parametrisation procedures in STEAM in this study and in previous studies. In the original version of STEAM (Wang-Erlandsson et al., 2014, 2016), each land cover (L) is simulated for the whole world ("mosaic"), and the total terrestrial evaporation (E) is obtained by weighing each land cover's evaporation (E_L) by its fractional spatial occupation (ϕ_L): $E = \Sigma E_L \phi_L$. In the coupled version of STEAM-WAM, we instead weigh each land cover specific parameter (p_L) with the land cover fractional occupation within each group of land-use or land-cover type. This merged land cover parametrisation map (p) is then used to simulate total evaporation ("mosaic-tile"): $E(p) = E(\Sigma p_L \phi_L)$.

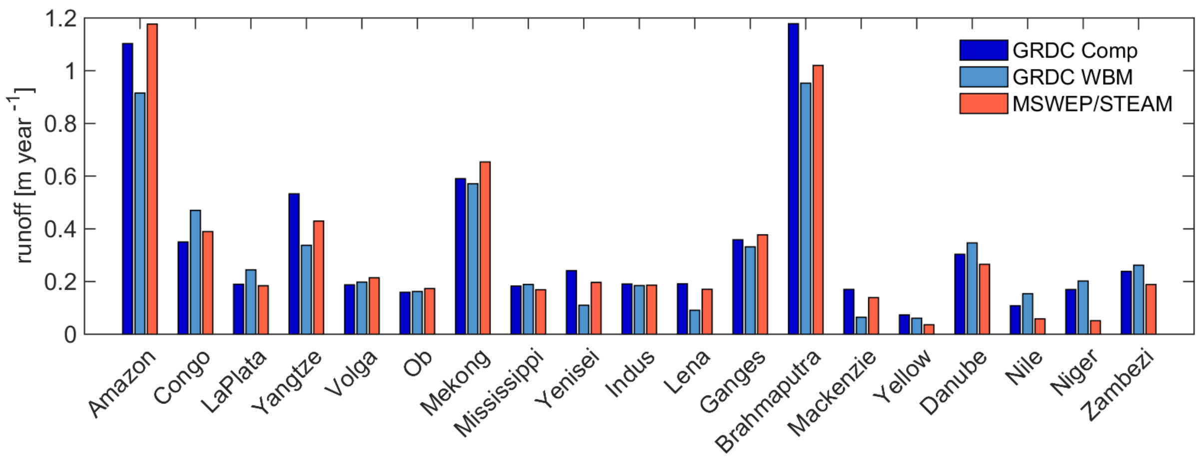

Figure S2. River flow validation. Comparison of simulated runoff (MSWEP/STEAM) with GRDC composite (GRDC Comp) and water balance model (GRDC WBM) runoff. MSWEP/STEAM deviates less from GRDC Comp (standard deviation σ = 0.0622 m yr^{-1}) than GRDC WBM (σ = 0.09993 m yr^{-1}). Note that GRDC runoff values not necessarily represent the best available observation data. For example in the River Niger, the GRDC discharge is around 0.2 m/y (Fig S8), while station data at Lokoja station for 1980-2013 shows that it is about 0.07 m/y (Oyerinde et al., 2017).

Table S3. Overview of studies of land-use induced changes in evaporation. Pure irrigation studies are included in this comparison with irrigation water consumption reported as "*E* increase".

		E decreases		*E* increases		Overall *E* change	
Reference	Model; Prec. forcing	km^3 y^{-1}	%	km^3 y^{-1}	%	km^3 y^{-1}	%
(Döll and Siebert, 2002)	WaterGAP; CRU	-	-	+1100	-	-	-
(Gordon et al., 2005)	Reference E; UDEL	-3000	- 4.5	+2600	+3.9	- 400	- 0.6
(Rost et al., 2008b)	LPJmL; HadCM3/CRU	-2360	- 3.8	+1325	+2.2	-1036	- 1.7
(Sterling et al., 2012)	ORCHIDEE; NgoDuc05	-	-	-	-	- 3160	- 5.6
(Sterling et al., 2012)	Literature-GIS; -	-2800	-4.2	+750	+1.1	- 3500	- 5.3
(Wada et al., 2014)	PCR-GLOBWB; CRU	-	-	+1179	-	-	-
(Wada et al., 2014)	PCR-GLOBWB; ERA-I	-	-	+1120	-	-	-
(Wada et al., 2014)	PCR-GLOBWB; MERRA	-	-	+994	-	-	-
(Wang-Erlandsson et al., 2014)	STEAM; ERA-I	-	-	+1134	+1.5	-	-
(Jägermeyr et al., 2016)	LPJmL; GPCC	-	-	+1268	-	-	-
This study	STEAM; MSWEP	-2047	-3.0	+796	+1.2	- 1251	- 1.8

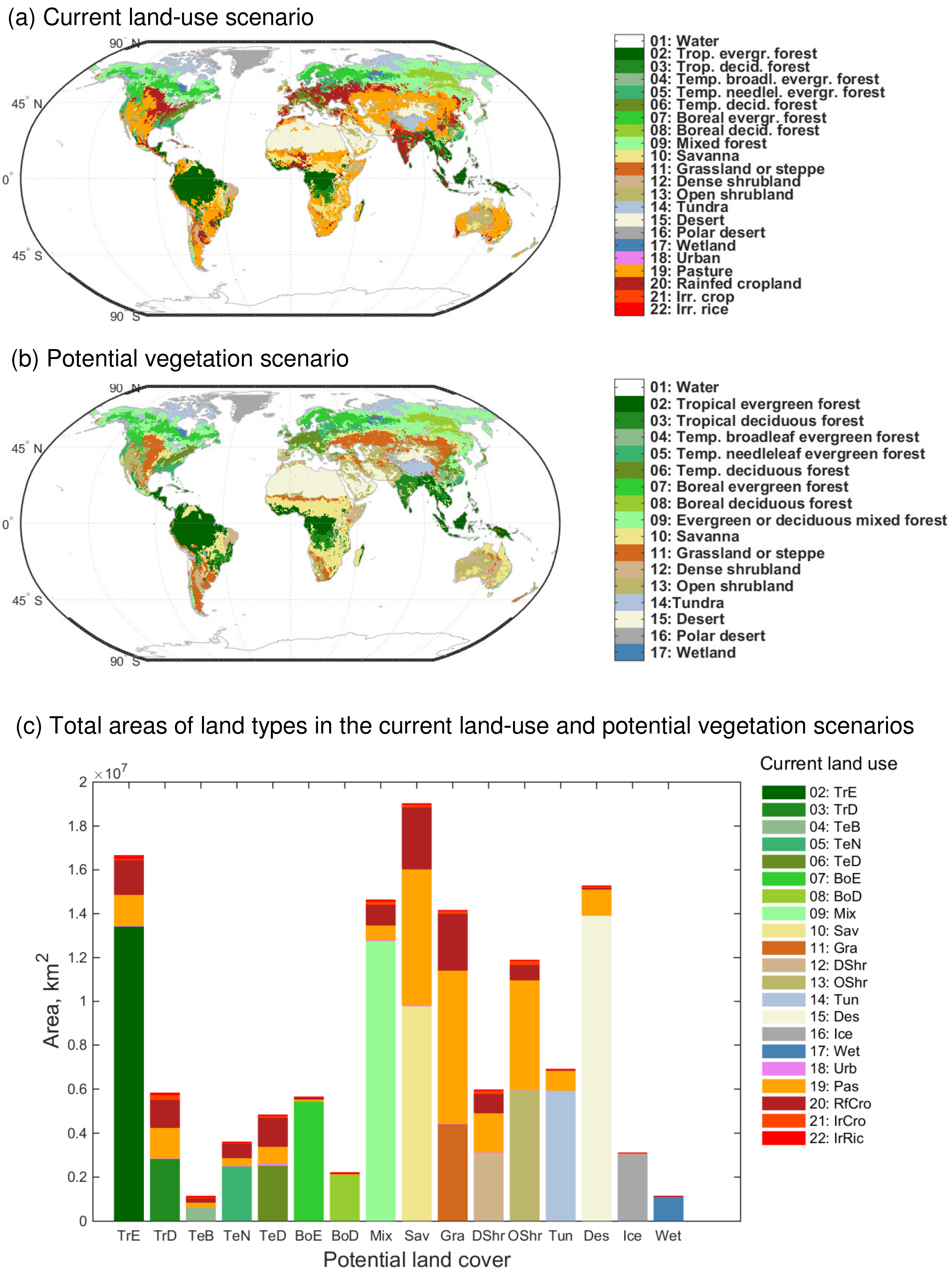

Figure S3. Land-use scenarios used in this study: a, current land use based on Ramankutty et al., (2008), MODIS, and MIRCA2000 (predominant land type shown, and irrigated areas represent the maximum extent over a year), **b**, potential vegetation based on Ramankutty and Foley, (1999) and MODIS, and **c**, total areas of different vegetation and land-use types.

Table S4. Overview of literature sources estimating human impact on river flows included in Fig. 5. Literature sources included are either global studies of potential land cover to current land use, or transient studies of river flow changes over the 20th century. Studies without global coverage are not included in the comparison, e.g., Gedney et al., (2006), Findell et al. (2007), Alkama et al. (2013), Labat et al. (2004), and Dai et al. (2009) are excluded due to smaller land areas than other studies included. The results of Labat et al. (2004) have also been contested by later studies (Alkama et al., 2011; Legates et al., 2005; Milliman et al., 2008). Dai et al. (2009) also only covers river flow changes 1948-2004. We do not assume evaporation change to correspond to river flow change, unless authors explicitly endorse the translation. This excludes for example Gordon et al. (2005) and Boisier et al. (2014) from the inter-comparison.

	Type	Time	Method	River flow change
LUC				
R08a(Rost et al., 2008a)	PV - > Cur	1971-2000	Offline dynamic vegetation model LPJmL.	+1306 km^3 yr^{-1}
R08b(Rost et al., 2008b)	PV - > Cur	1991-2000	Offline dynamic vegetation model LPJmL.	+1770 km^3 yr^{-1}
S12(Sterling et al., 2012)	PV - > Cur	Mixed	Literature and statistical modelling in GIS.	+3500 km^3 yr^{-1}
S12(Sterling et al., 2012)	PV - > Cur	1950-2000	Offline land surface model ORCHIDEE.	+3869 km^3 yr^{-1}
P07(Piao et al., 2007)	20th century	1901-1999	Offline land surface model ORCHIDEE.	+1089 km^3 yr^{-1}
G08(Gerten et al., 2008)	20th century	1901-2002	Offline dynamic vegetation model LPJmL. Trend from land-use change simulation using CRU precipitation.	+680 km^3 yr^{-1}
Climate change				
P07(Piao et al., 2007)	20th century	1901-1999	Offline land surface model ORCHIDEE. Climate change excluding CO_2 effect.	+1771 km^3 yr^{-1}
G08(Gerten et al., 2008)	20th century	1901-2002	Offline dynamic vegetation model LPJmL. Trend from precipitation P and temperature T change simulation using CRU precipitation.	+2600 km^3 yr^{-1} (P), -360 km^3 yr^{-1} (T), +2240 km^3 yr^{-1} (P+T)
A10(Alkama et al., 2010)	20th century	1901-2000	Offline land surface model ORCHIDEE. Climate change effect only.	+2477 km^3 yr^{-1}
CO_2 effect				
P07(Piao et al., 2007)	20th century	1901-1999	Offline land surface model ORCHIDEE. CO_2 allowing LAI change.	-545 km^3 yr^{-1}
G08(Gerten et al., 2008)	20th century	1901-2002	Offline dynamic vegetation model LPJmL. Trend from CO_2 simulation.	+480 km^3 yr^{-1}
A10(Alkama et al., 2010)	20th century	1901-2000	Offline land surface model ORCHIDEE. CO_2 effect only.	+275 km^3 yr^{-1}
Water consumption				
R08a(Rost et al., 2008a)	PV - > Cur	1971-2000	Offline dynamic vegetation model LPJmL. Excluding nonlocal blue water (ILIM).	-457 km^3 yr^{-1}
G08(Gerten et al., 2008)	20th century	1901-2002	Offline dynamic vegetation model LPJmL. Trend from irrigation simulation.	-120 km^3 yr^{-1}
D09(Döll et al., 2009)	PV - > Cur	2002	Offline hydrological model WaterGAP.	-1300-1400 km^3 yr^{-1}
S12(Sterling et al., 2012)	PV - > Cur	Mixed	Literature review of withdrawal. Assuming water consumption to be 52 % of total withdrawal.	-1250 km^3 yr^{-1}
J15(Jaramillo and Destouni, 2015)	20th century	1901-1954 vs. 1955-2008	Analyses of hydroclimatic data for 100 large basins (35 % global land area).	-4370 km^3 yr^{-1} (±979 km^3 yr^{-1})
Overall human impact				
G08(Gerten et al., 2008)	20th century	1901-2002	Offline dynamic vegetation model LPJmL. Sum of precipitation, temperature, land-use change, CO_2, irrigation effect.	+3280 km^3 yr^{-1}
S12(Sterling et al., 2012)	Mixed	Mixed	Mean change from literature review.	+1500 km^3 yr^{-1}

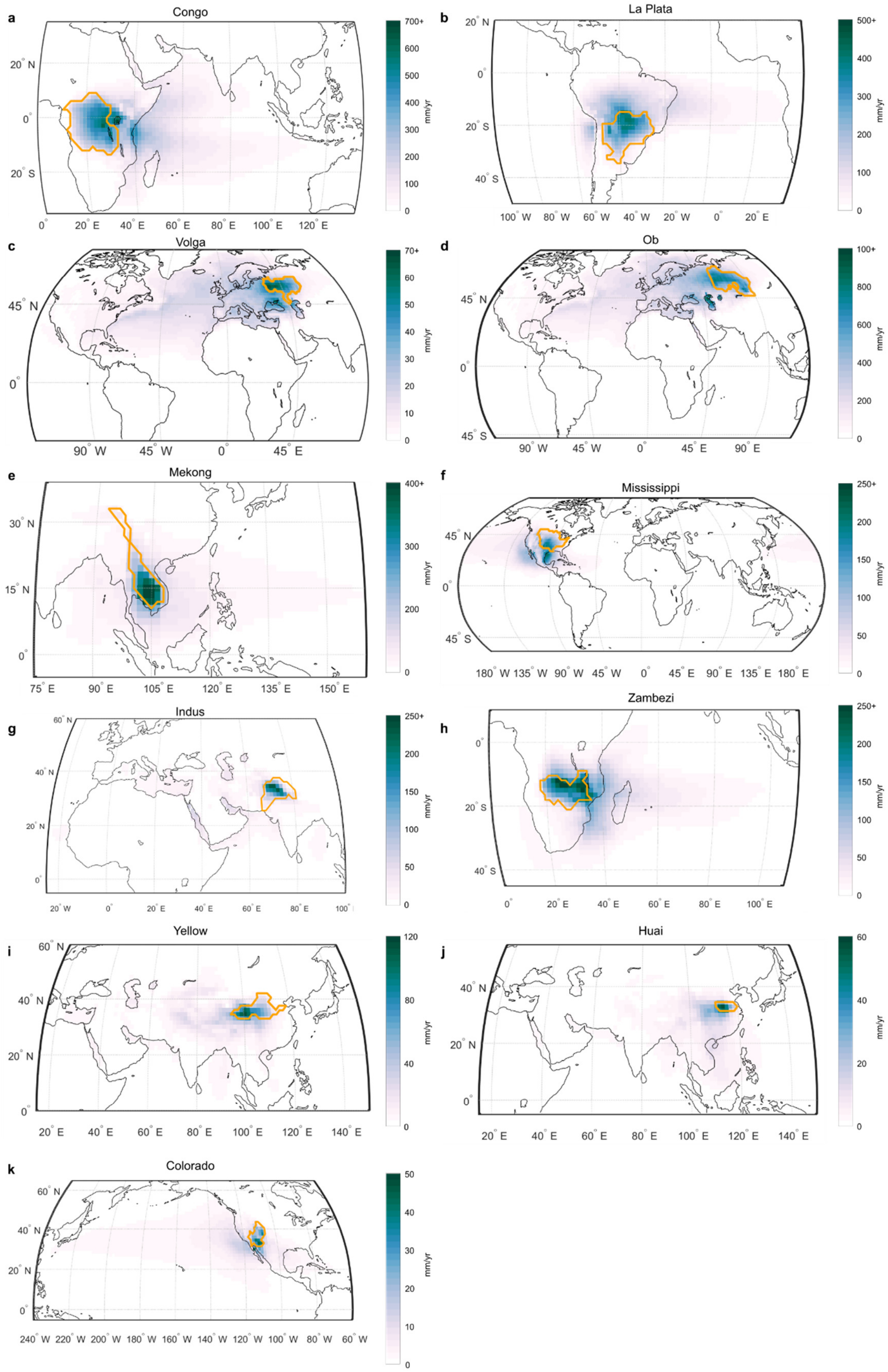

Figure S4. Mean annual precipitation sources for selected river basins (boundaries in orange).

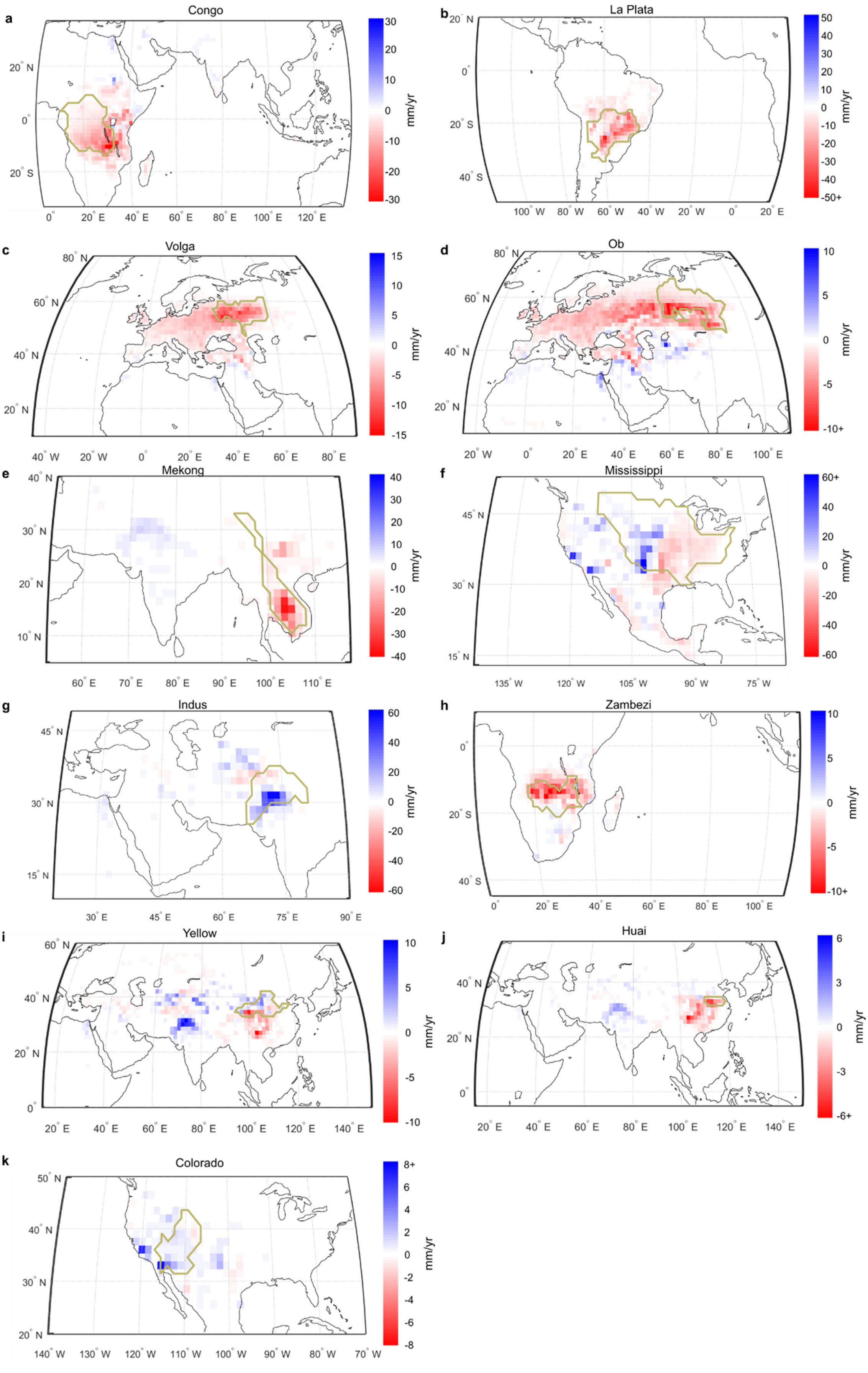

Figure S5. Impacts of human land-use change on mean annual precipitation source (i.e., $\Delta P_{\text{import}} + \Delta P_{\text{basin-recycling}}$) for selected river basins (boundaries in dark yellow).

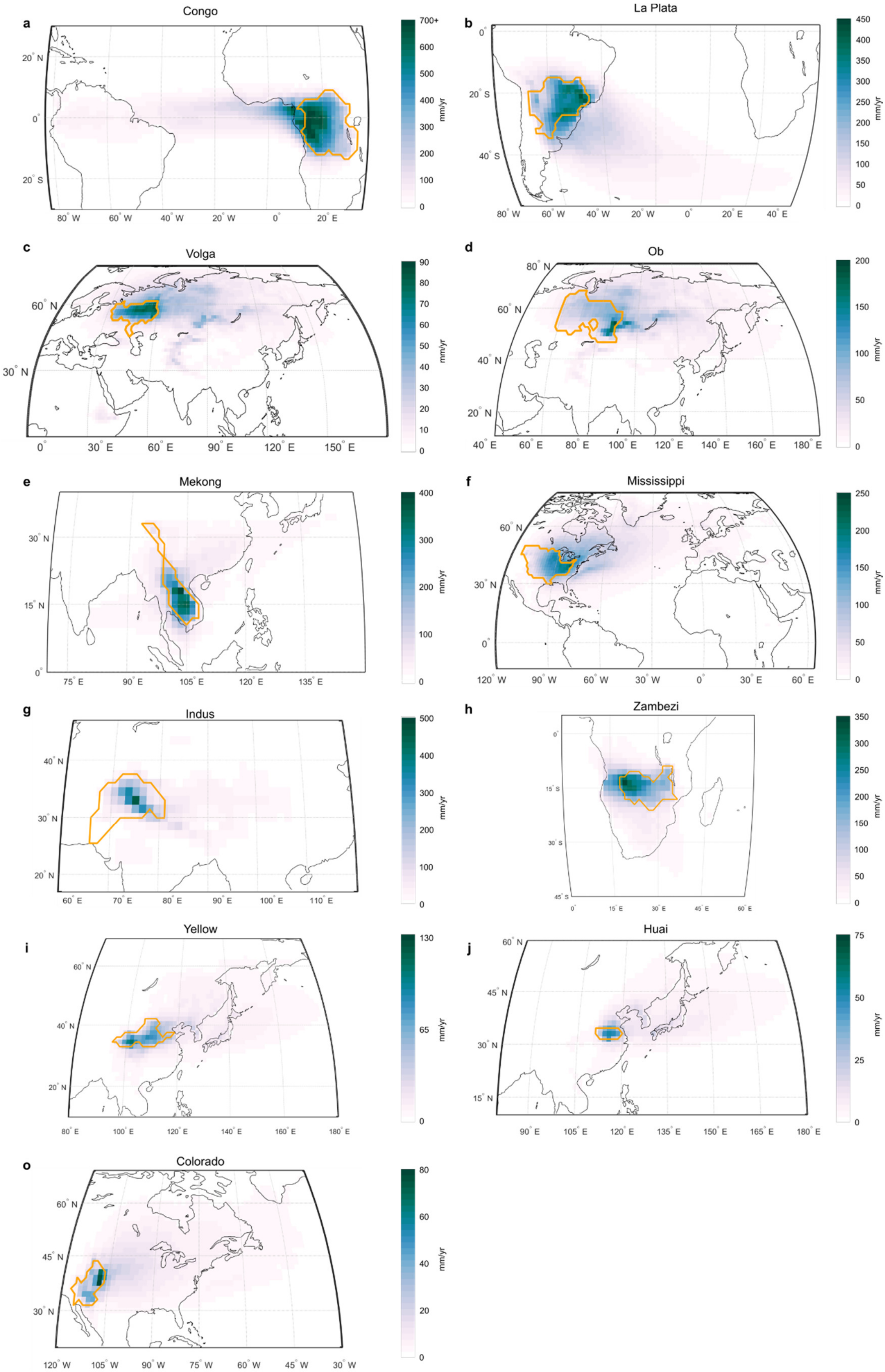

Figure S6. Mean annual evaporation sinks for selected river basins (boundaries in orange).

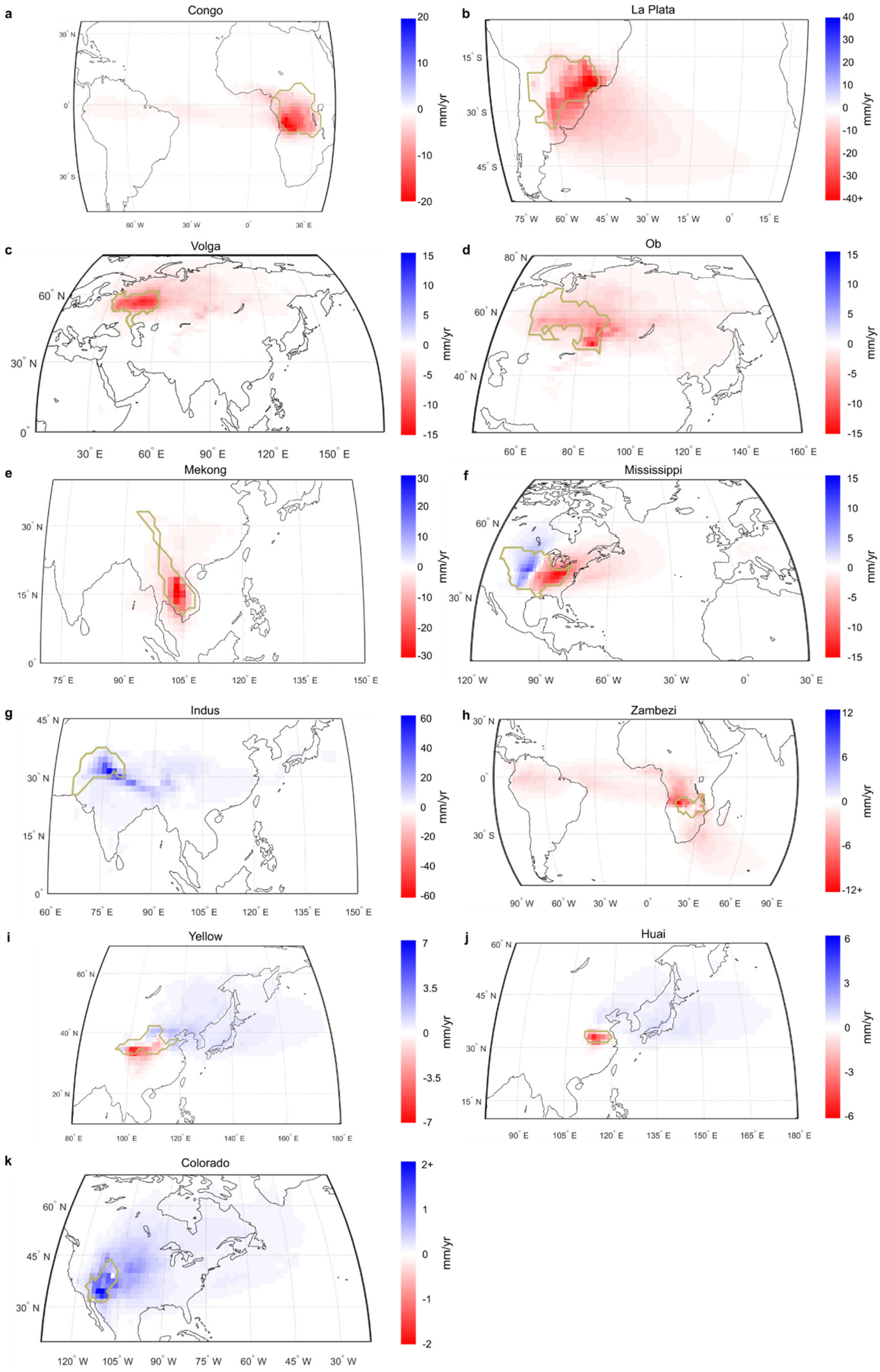

Figure S7. Impacts of human land-use change on mean annual evaporation sink (i.e., ΔE_{export} + $\Delta E_{basin\text{-}recycling}$) for selected river basins (boundaries in dark yellow).

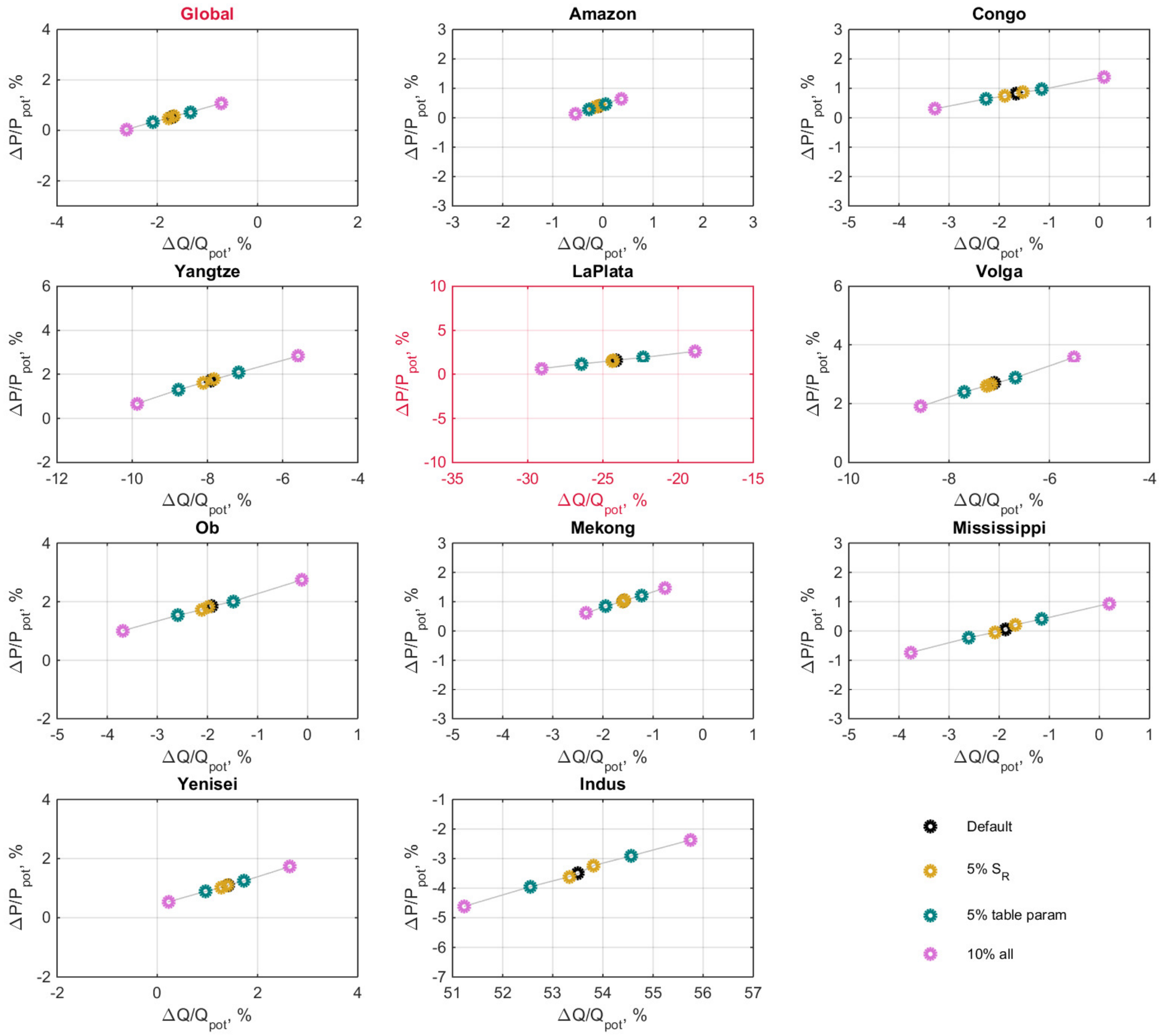

Figure S8. Sensitivity analysis. The relationship between annual mean precipitation change and river flow change under different perturbations of STEAM parameter values in pasture and croplands. The three different sets of perturbation experiments are: 5 % increase and decrease of root zone storage capacity S_R (green circles), 5% perturbation of six tabulated land parameters in a direction that causes either increase or decrease in evaporation (blue circles), and 10 % perturbation of both S_R and the six tabulated land parameters in a direction that causes either increase or decrease in evaporation (purple circles). Note that in each experiment, the parameter values are perturbed in the same direction in terms of increase or decrease in evaporation. The six look-up table parameters are maximum leaf area index LAI_{max}, minimum leaf area index LAI_{min}, albedo α, maximum plant height h_{max}, minimum plant height h_{min}, and minimum stomatal resistance $r_{st,min}$. Except for La Plata, the different plots have identical scales and can therefore be compared to each other. Evaporation simulation in Mississippi and Indus can be slightly sensitive to initial soil moisture conditions (not shown). Presented results are from simulations for the years 2000-2002.

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