remote sensing

MDPI

Supplementary materials

Spatiotemporal Dynamics of NDVI, Soil Moisture and ENSO in Tropical South America

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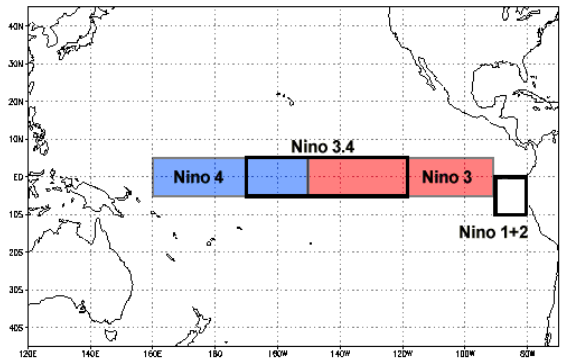


Figure S1. Location of the distinctive regions along the tropical Pacific commonly used to study the dynamics of ENSO: Niño 4 (5°N-5°S, 160°E-150°W), Niño 3.4 (5°N-5°S, 170°W-120°W), Niño 3 (5°N-5°S, 150°W-90°W), and Niño 1+2 (0°-10°S, 90°W-80°W). Source: National Oceanic and Atmospherc Administration; https://www.noaa.gov.

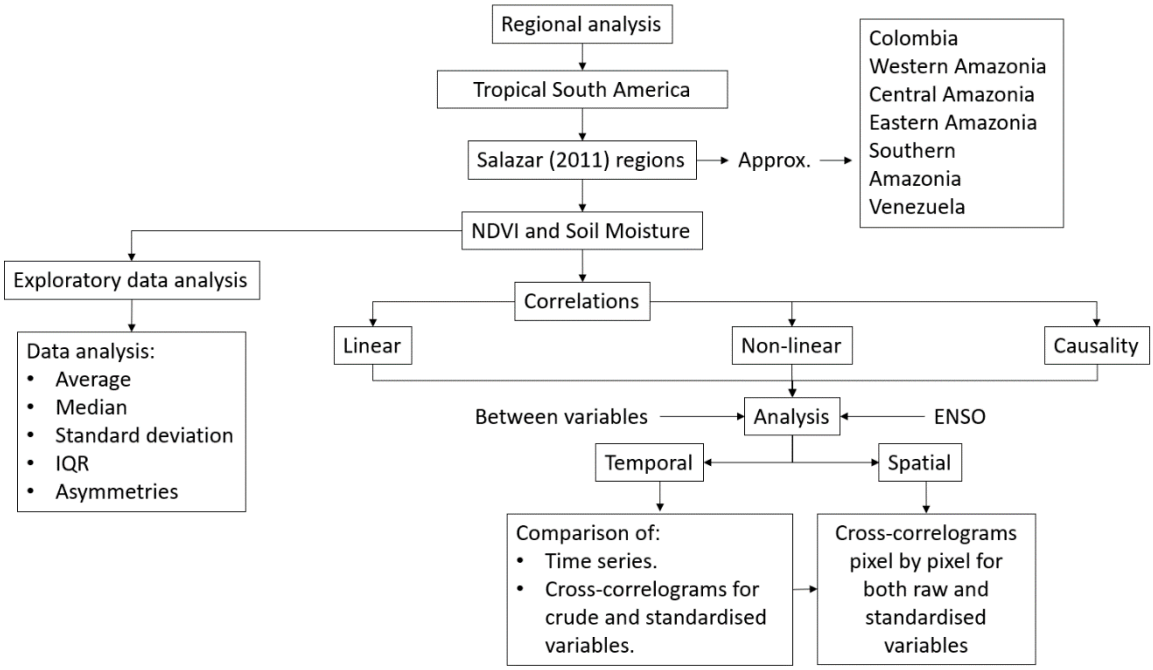


Figure S2. Workflow chart used in the study.

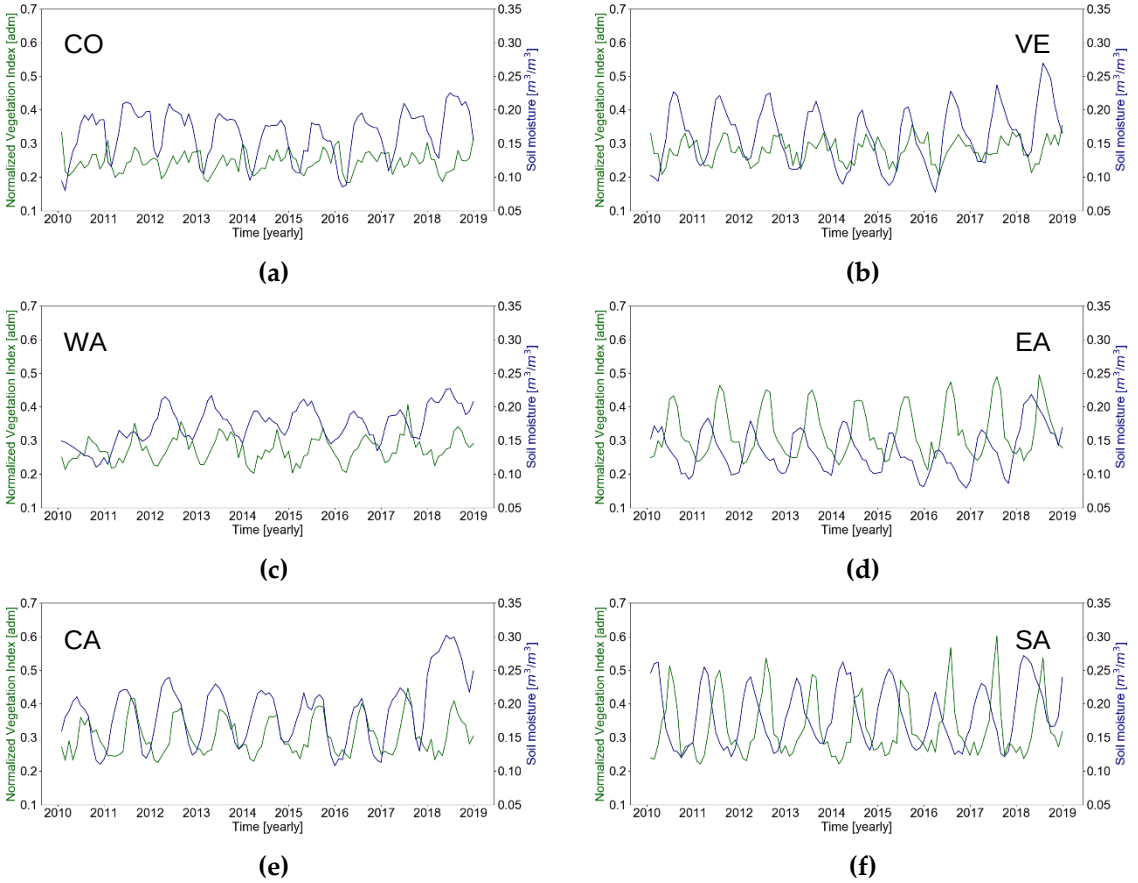
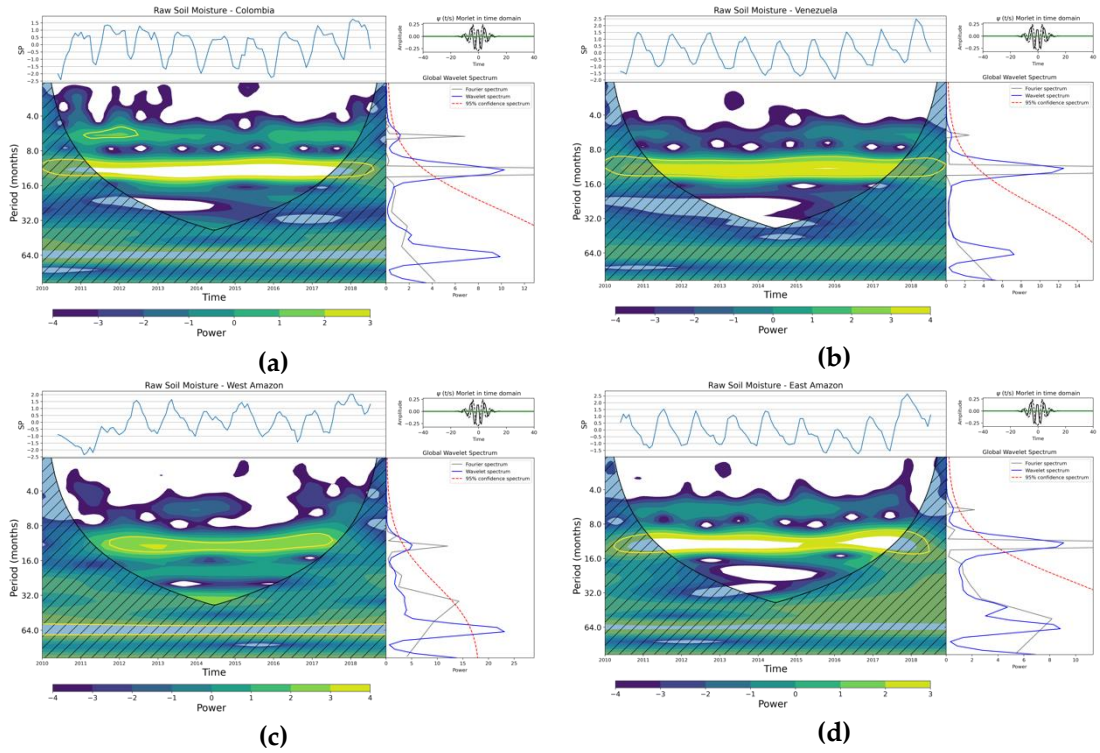


Figure S3. Time series of monthly values of NDVI (green) and soil moisture (blue) over the study regions. **(a)** CO – Colombia, **(b)** VE – Venezuela, **(c)** WA – West Amazonia, **(d)** EA – East Amazonia, **(e)** CA – Center Amazonia and **(f)** SA – South Amazonia.



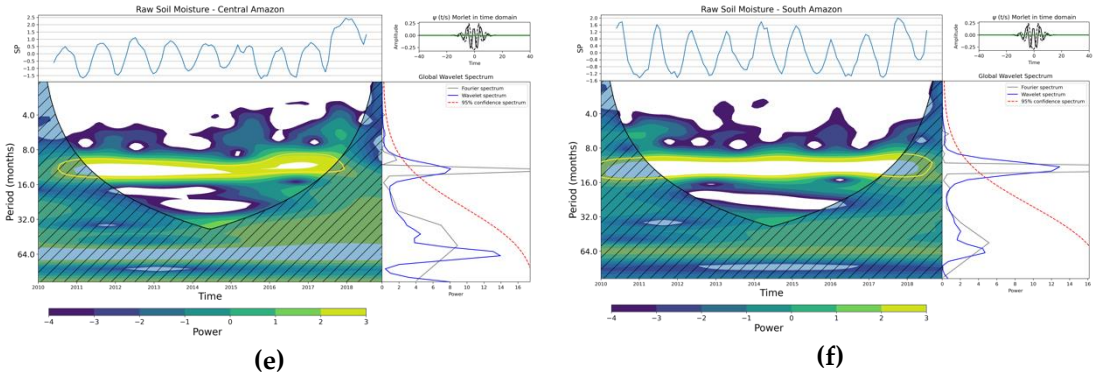


Figure S4. SMOS raw series Wavelets: **(a)** CO – Colombia, **(b)** VE – Venezuela, **(c)** WA – West Amazonia, **(d)** EA – East Amazonia, **(e)** CA – Center Amazonia and **(f)** SA – South Amazonia.

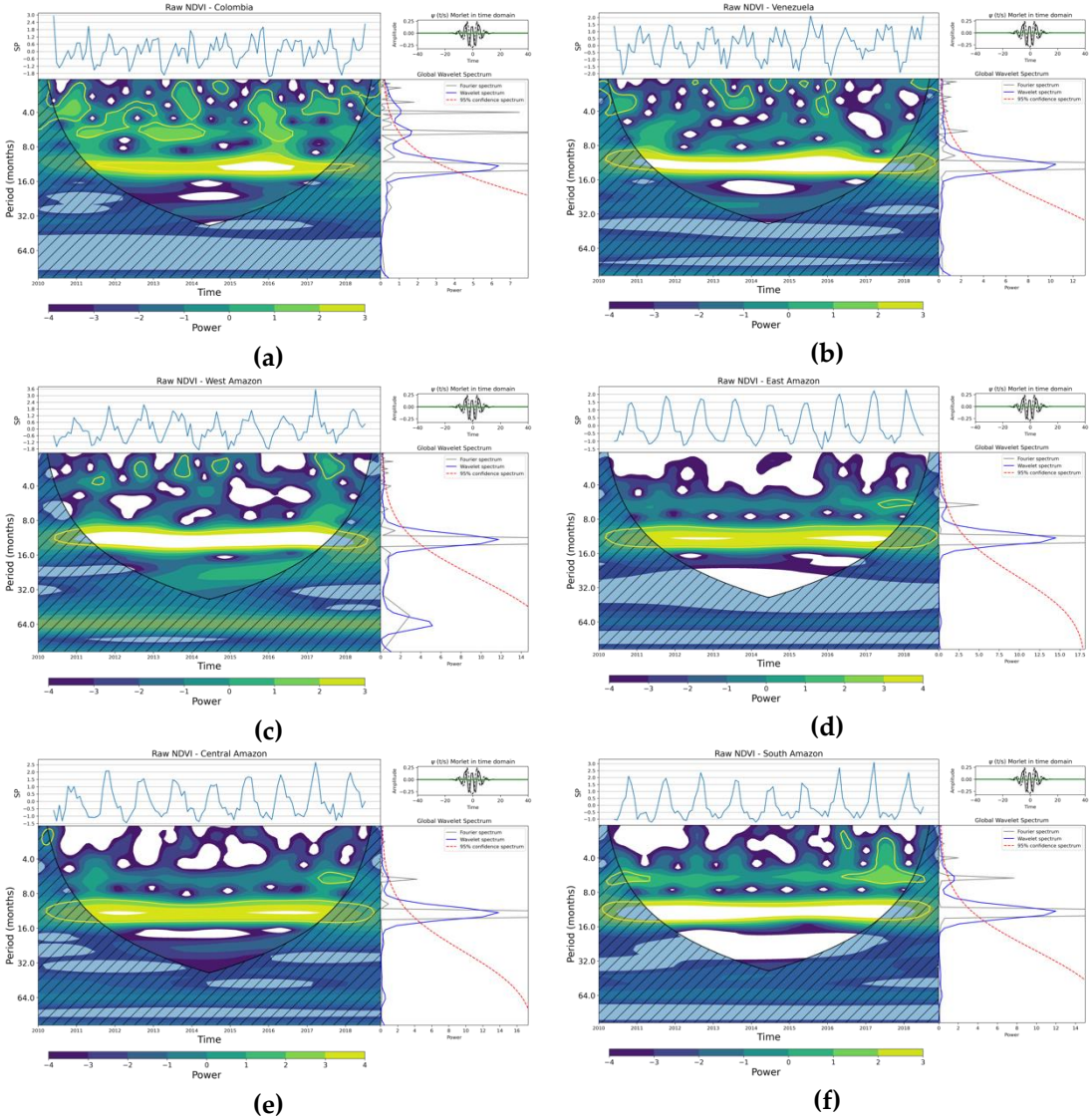


Figure S5. NDVI raw series Wavelets: (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.

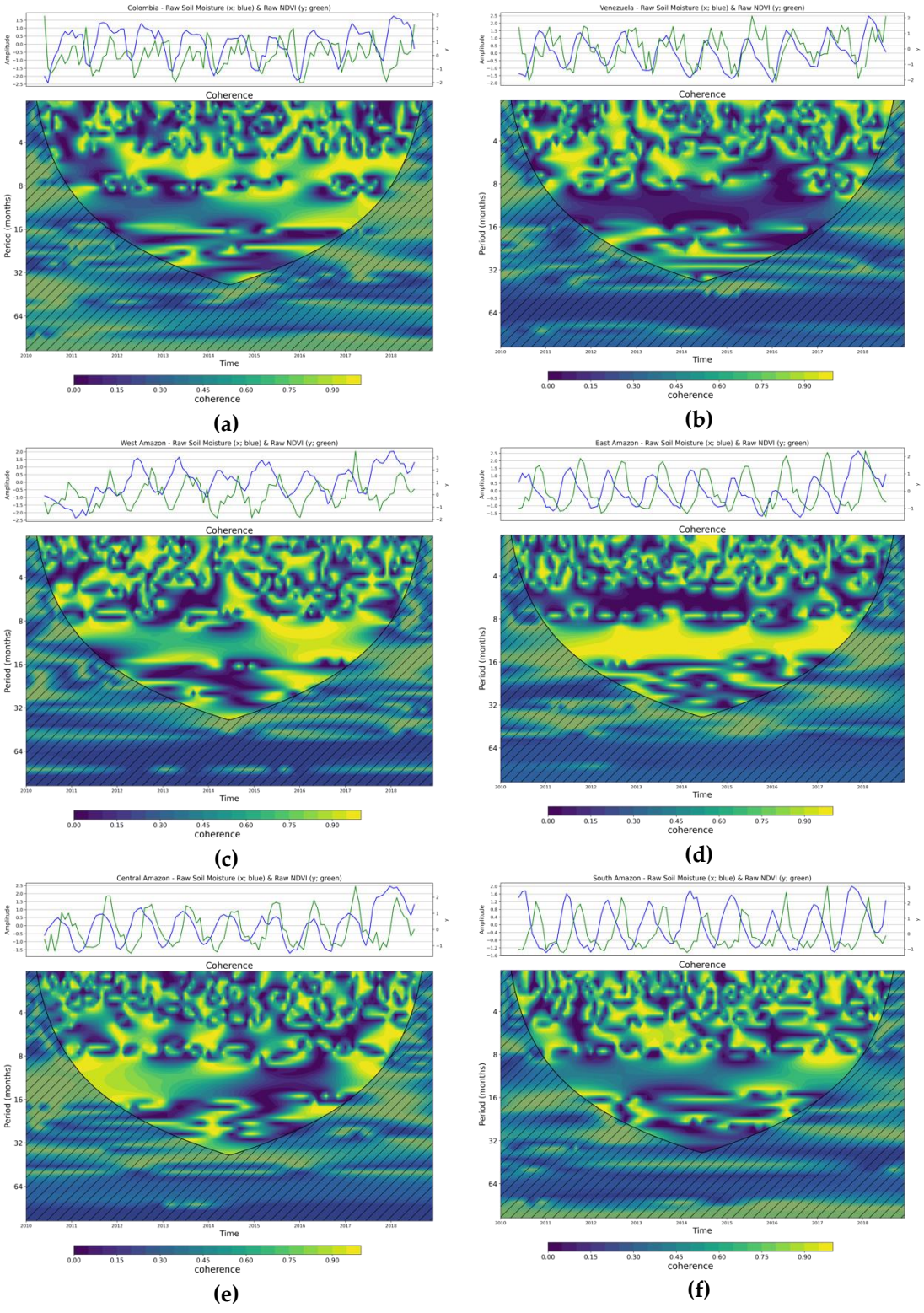


Figure S6. Wavelet coherency analyses between raw series of NDVI and SMOS for the six studied regions. The linear color scale results go from deep blue (WCO=0) to yellow (WCO=1): (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.

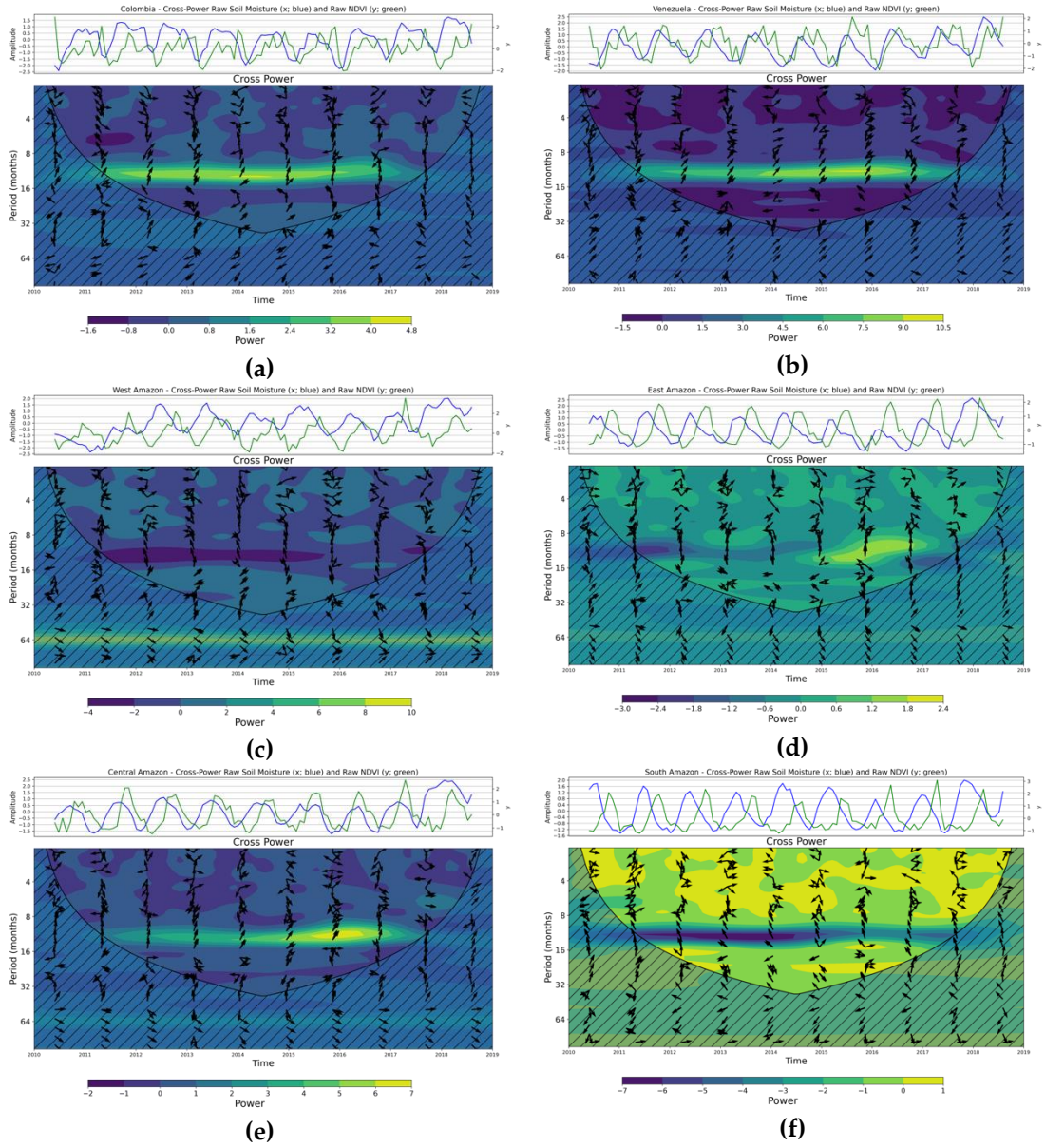
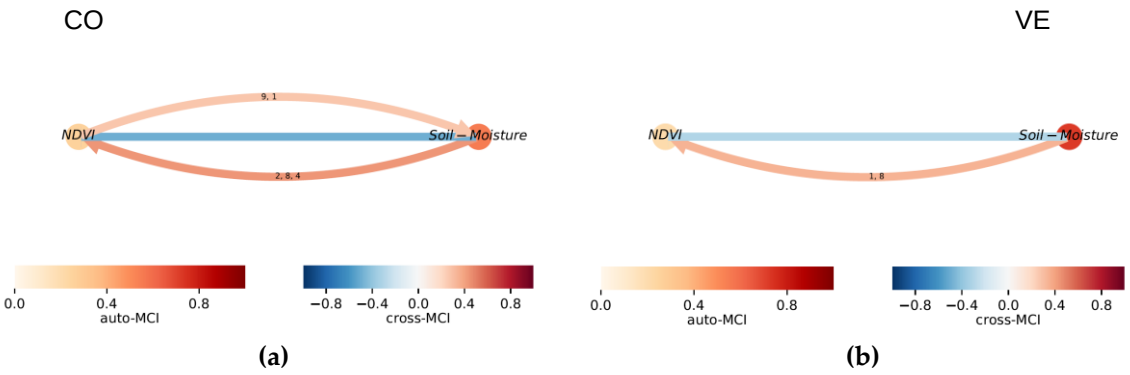


Figure S7. Wavelet cross-spectra analyses between raw series of NDVI and SMOS for the six studied regions. Arrows pointing to the right denote that both series are in phase, whereas pointing to the left denote that both series are out of phase: (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.



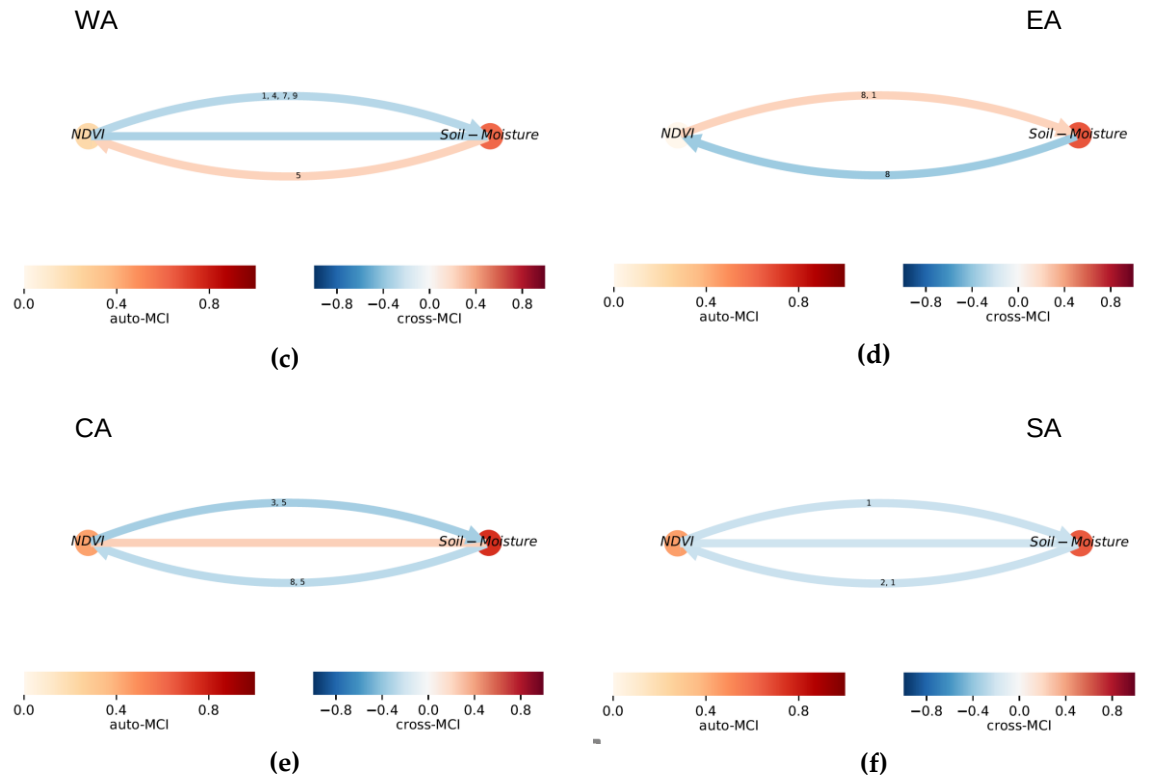


Figure S8. Non-linear causality analysis with ParrCorr method between NDVI and SMOS raw series. **(a)** CO – Colombia, **(b)** VE – Venezuela, **(c)** WA – West Amazonia, **(d)** EA – East Amazonia, **(e)** CA – Center Amazonia and **(f)** SA – South Amazonia.

Table S1. Non-linear causality correlations and causality results for ParrCorr method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.6	0.8	0.6	0.8	0.6	0.6
	NDVI	0.2	0.2	0.2	0.6	0.4	0.0
Sim. co-dependency[1]		-0.4	-0.2	-0.2	0.2	-0.2	-
Sim. co-dependency direction		-	-	-	-	-	-
Cross-MCI direction[2]		Both	S to N	Both	Both	Both	Both
Cross-MCI	SMOS	0.4	0.4	0.2	-0.2	-0.2	-0.4
	NDVI	0.2	-	-0.2	-0.4	-0.2	0.2
Cross-MCI lag*	SMOS	2,8,4	1,8	5	8,5	2,1	8
	NDVI	9,1	-	1,4,7,9	3,5	1	8,1

[1] Simultaneous non-linear co-dependency, * Direction refers to N= NDVI and S= SMOS

[2] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).

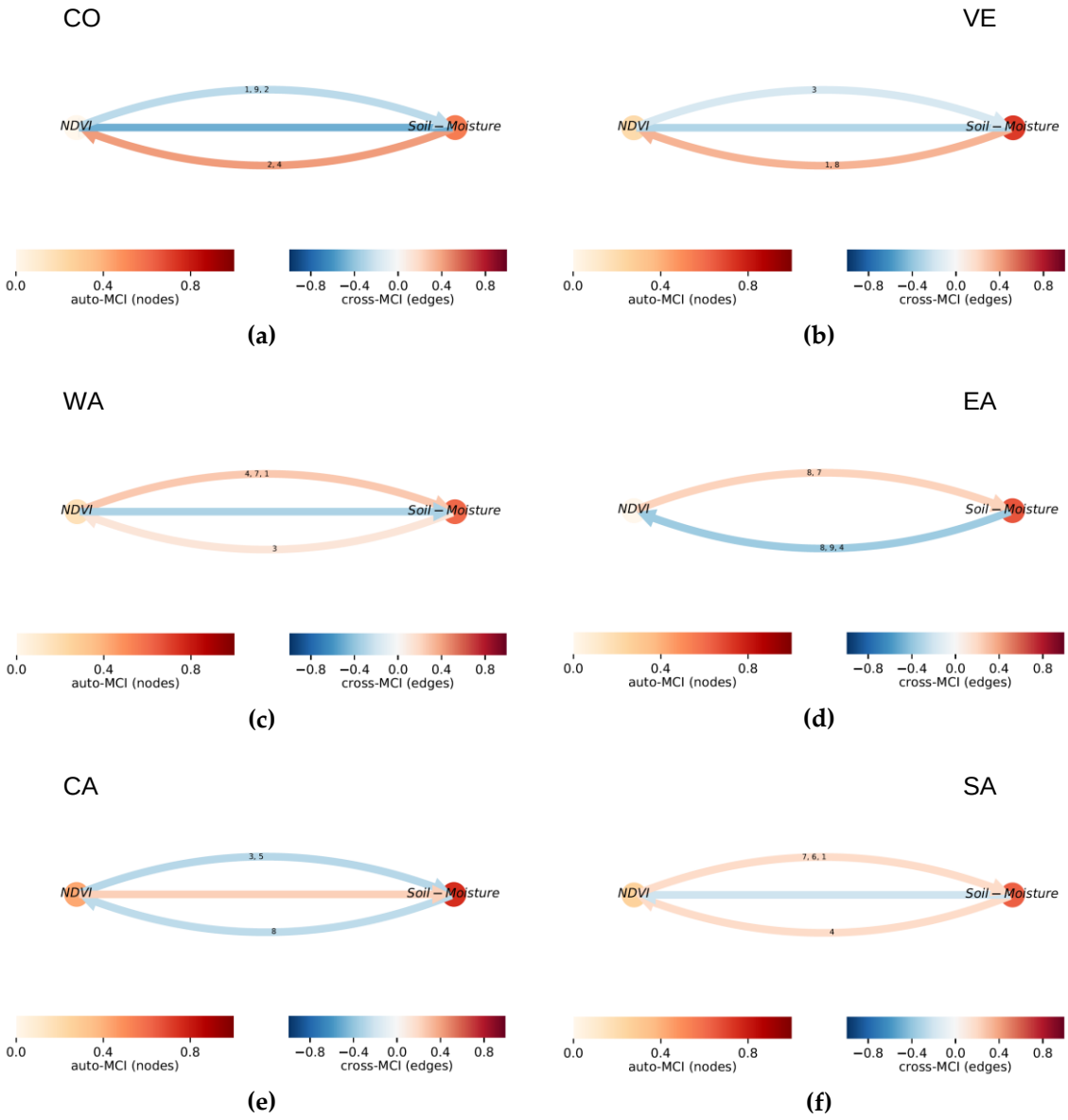


Figure S9. Non-linear causality analysis with PCMCIPLUS method between NDVI and SMOS raw series. **(a)** CO – Colombia, **(b)** VE – Venezuela, **(c)** WA – West Amazonia, **(d)** EA – East Amazonia, **(e)** CA – Center Amazonia and **(f)** SA – South Amazonia.

Table S2. Non-linear causality correlations and causality results for PCMCIplus method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.6	0.8	0.6	0.8	0.6	0.6
	NDVI	0.1	0.2	0.2	0.4	0.2	0.1
Sim. co-dependency[1]		-0.4	-0.6	-0.2	-0.2	0.2	-0.1
Sim. co-dependency direction		-	-	-	N to S	N to S	S to N
Cross-MCI direction[2]		-	Both	Both	Both	Both	Both
Cross-MCI correlation	SMOS	0.6	0.4	0.2	-0.2	0.2	-0.4
	NDVI	-0.2	-0.1	0.4	-0.2	0.2	0.2
Cross-MCI lag*	SMOS	2,4	1,8	3	8	4	8,9,4
	NDVI	1,9,2	3	4,7,1	3,5	7,6,1	8,7

[1] Simultaneous non-linear co-dependency, * Direction refers to N= NDVI and S= SMOS

[2] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).

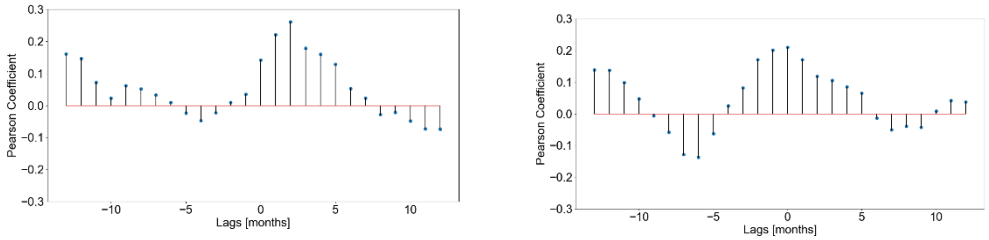
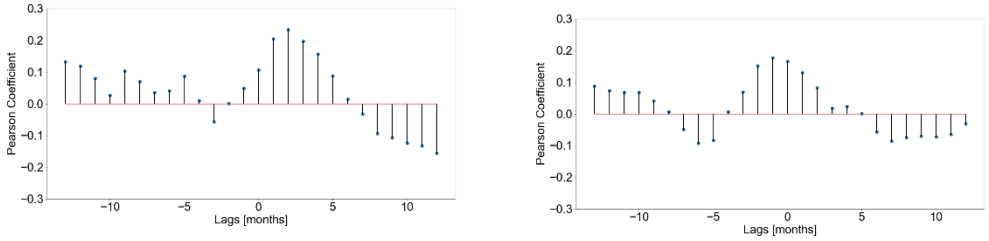
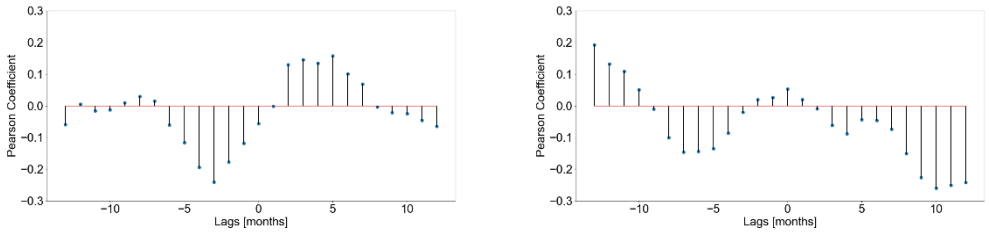
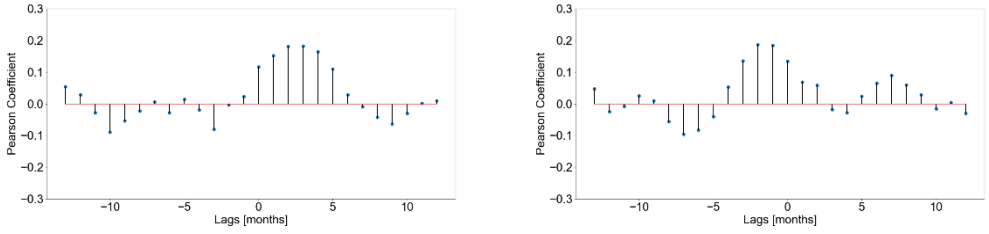
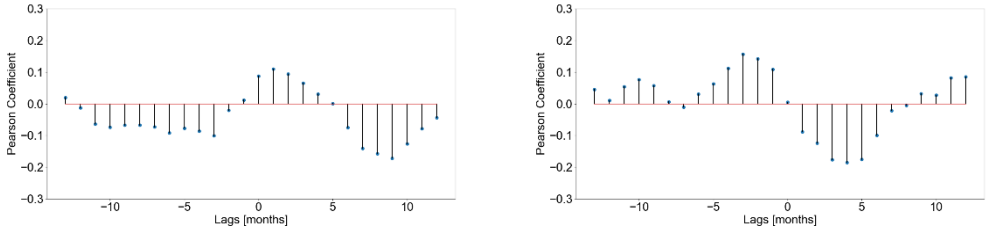
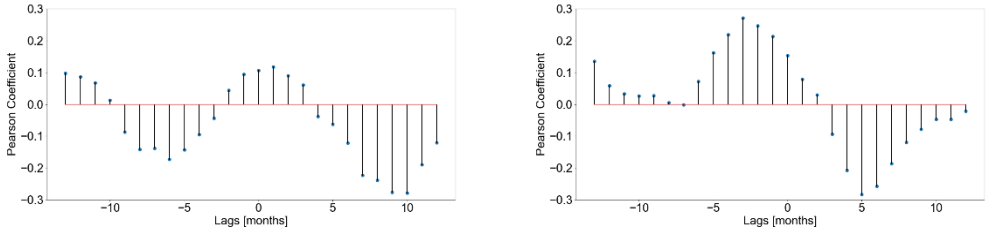
Region	CP	EP
CO		
VE		
WA		
CA		
EA		
SA		

Figure S10. Comparison between NDVI correlations with ENSO CP and EP indices.

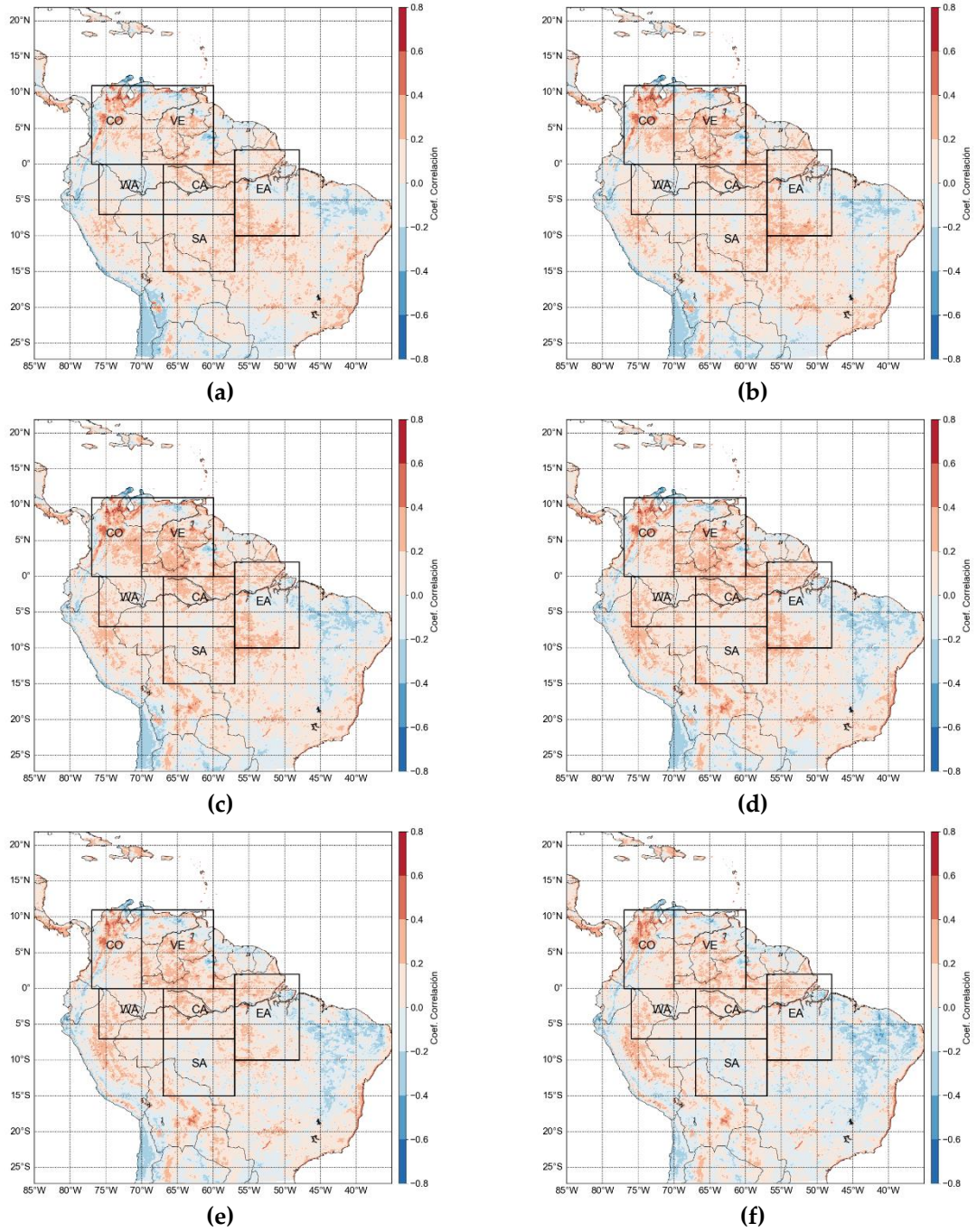


Figure S11. Spatial lagged-correlations between the CP index (leading) and standardized NDVI (lagging) monthly data: (**a**) 0 lag; (**b**) 1-month lag; (**c**) 2-months lag; (**d**) 3-months lag; (**e**) 4-months lag; and (**f**) 5-months lag.

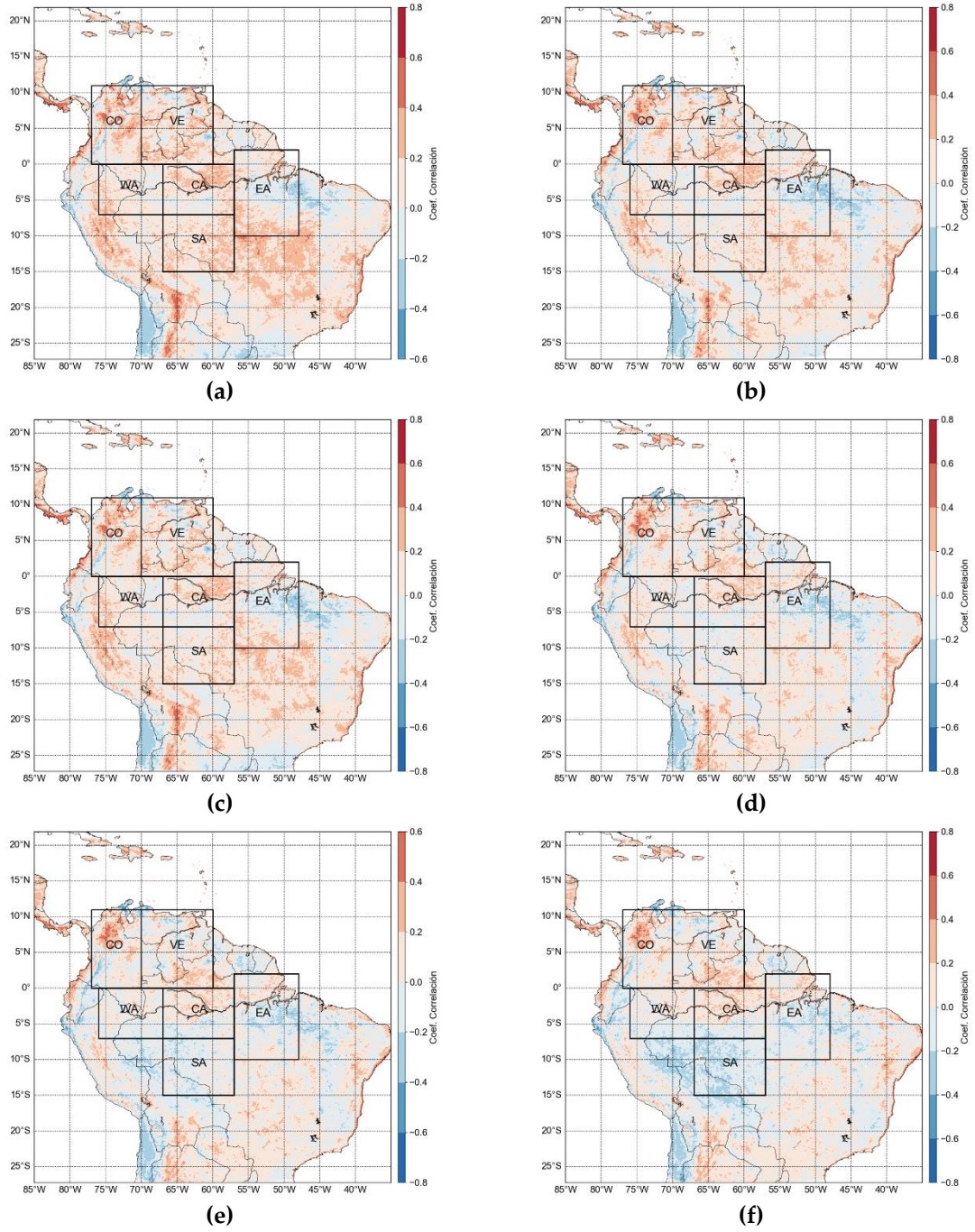


Figure S12. Spatial lagged-correlations between the EP index (leading) and standardized NDVI (lagging) monthly data: (**a**) 0 lag; (**b**) 1-month lag; (**c**) 2-months lag; (**d**) 3-months lag; (**e**) 4-months lag; and (**f**) 5-months lag.

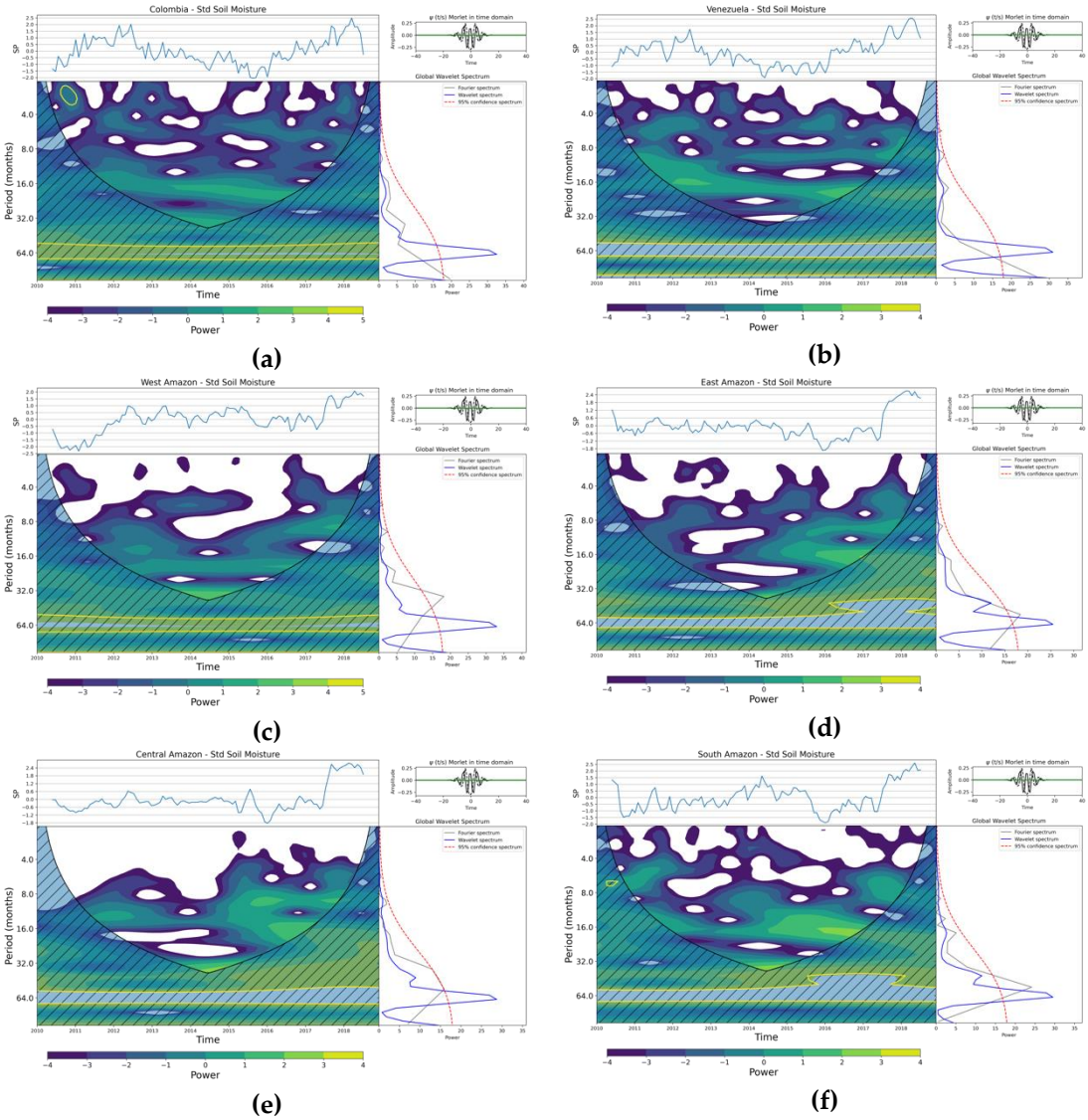
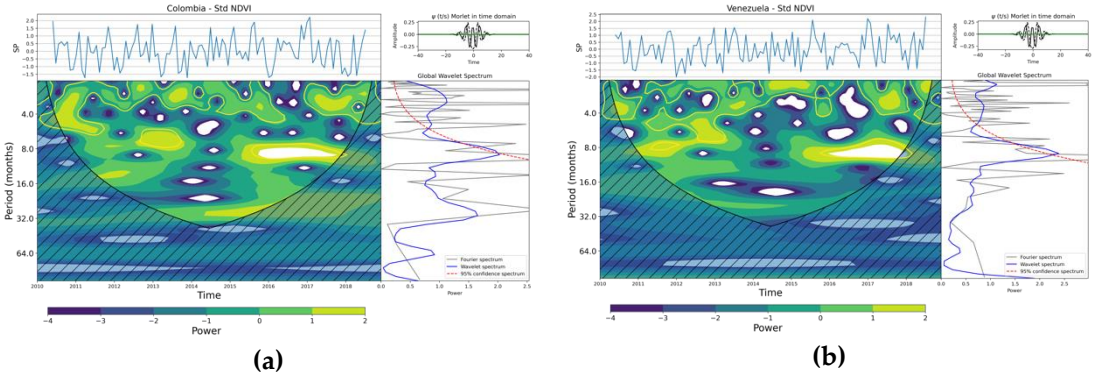


Figure S13. SMOS standardized series Wavelets: (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.



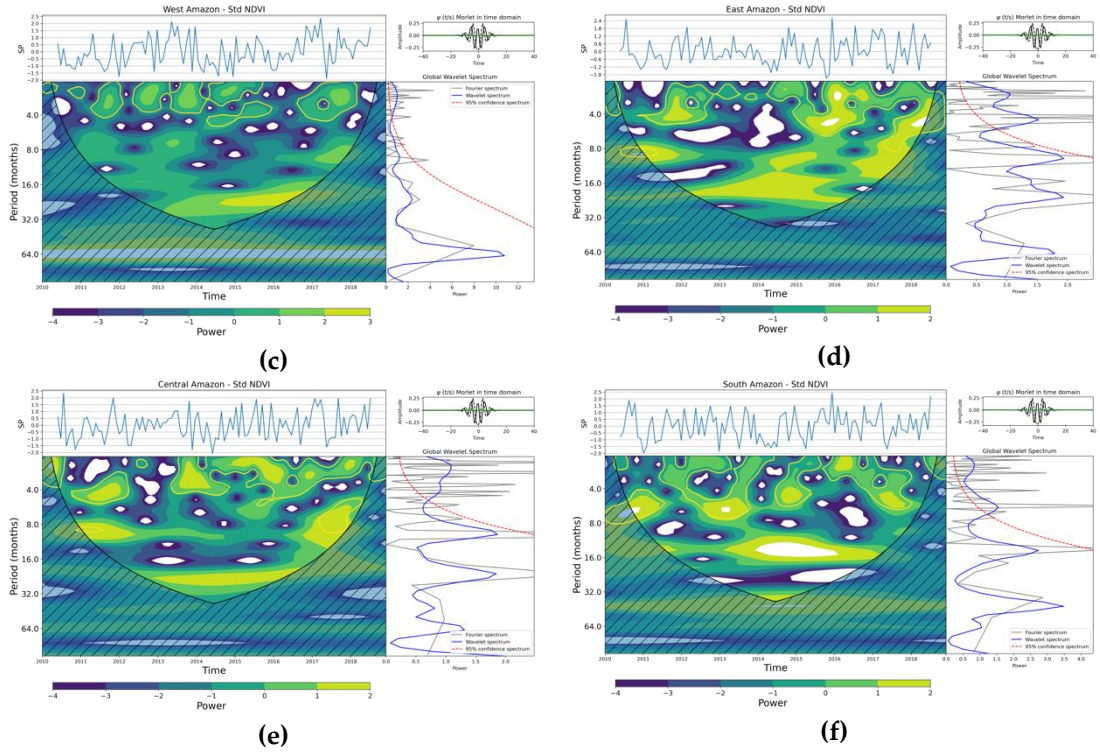
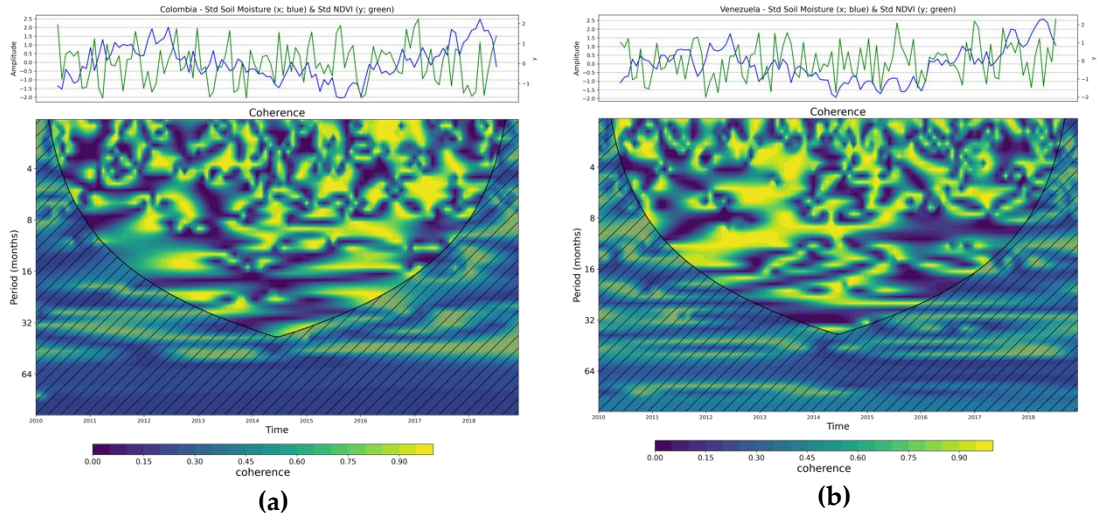


Figure S14. NDVI standardized series Wavelets: (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.



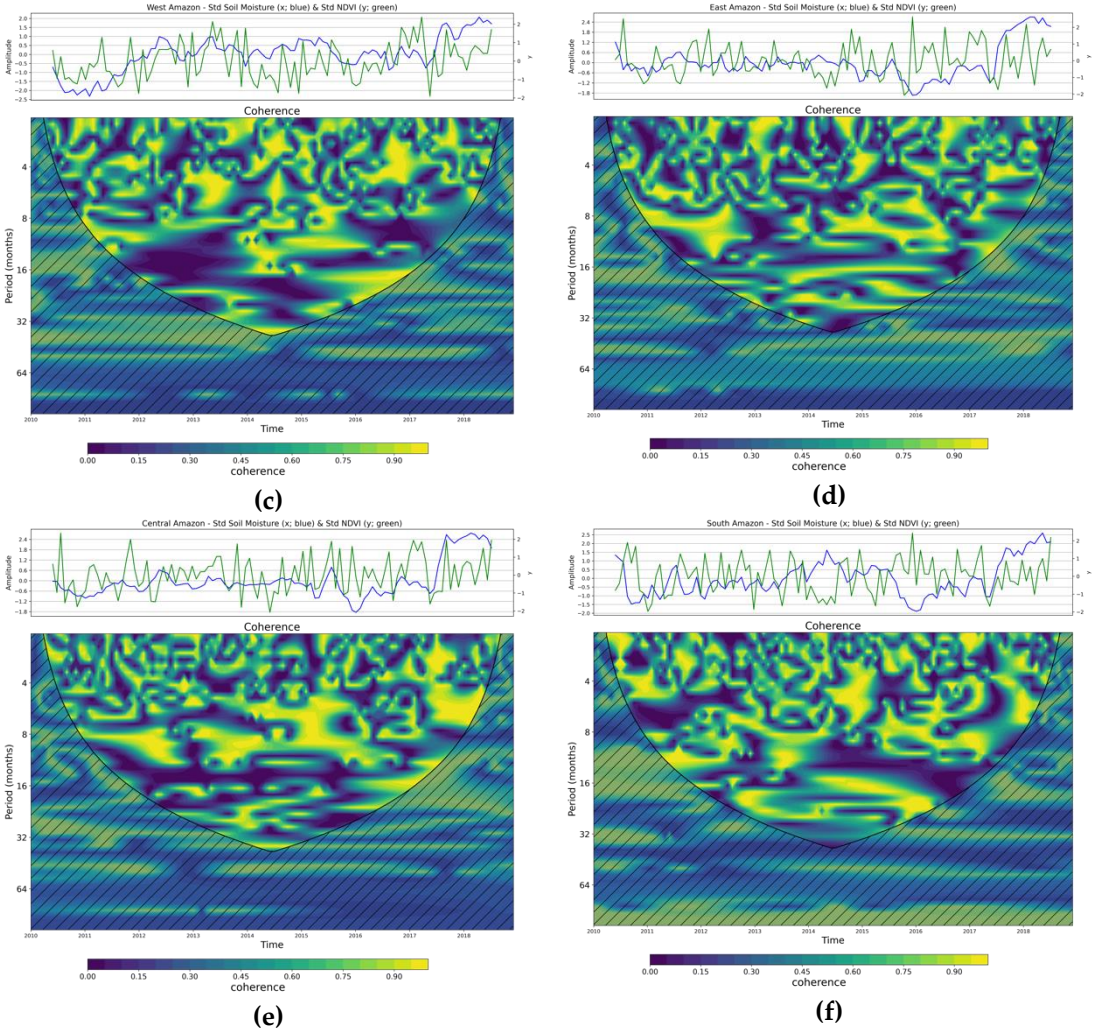
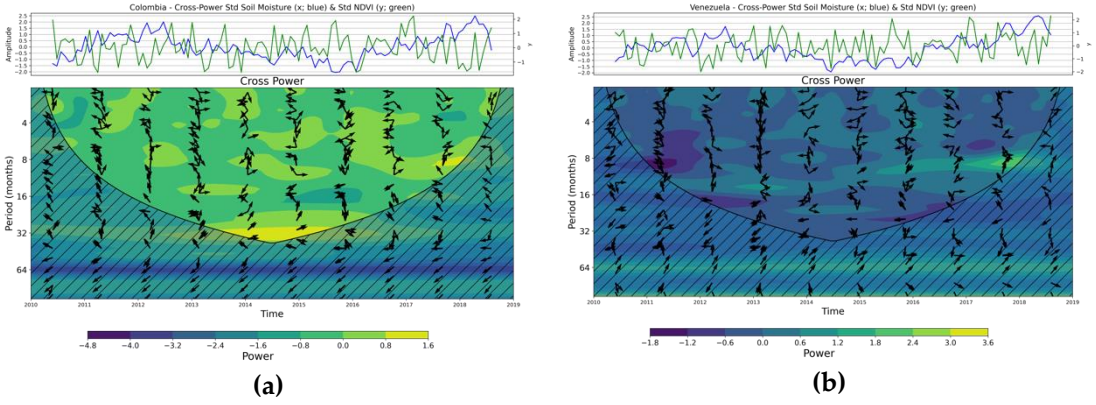


Figure S15. Wavelet coherency analyses between standardized series of NDVI and SMOS for the six studied regions. The linear color scale results go from deep blue (WCO=0) to yellow (WCO=1): (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.



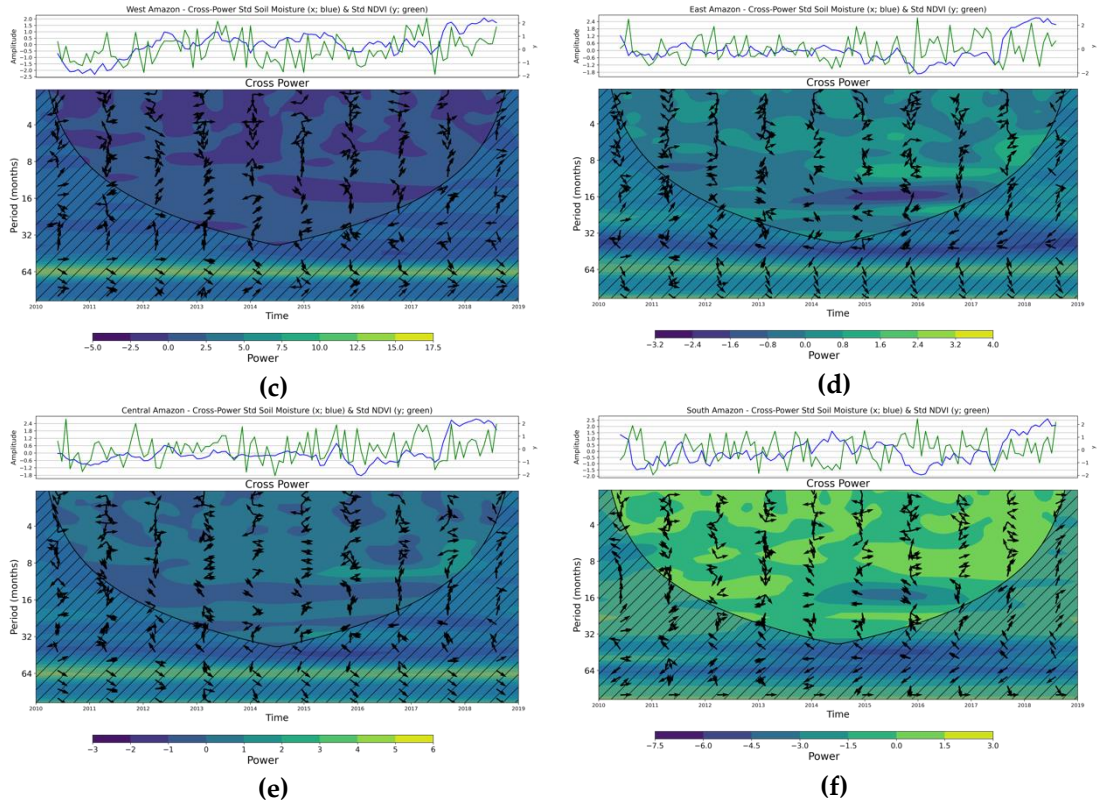


Figure S16. Wavelet cross-spectra analyses between standardized series of NDVI and SMOS for the six studied regions. Arrows pointing to the right denote that both series are in phase, whereas pointing to the left denote that both series are out of phase: (a) Colombia; (b) Venezuela; (c) West Amazon; (d) East Amazon; (e) Central Amazon; (f) South Amazon.

Table S3. Non-linear correlations and causality results for CP index, ParrCorr method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.6	0.6	0.6	0.6	0.6	0.6
	NDVI	0.1	0.4	0.4	0.1	0.1	0.1
	CP	0.8	0.8	0.8	0.8	0.8	0.8
Sim. co-dependency[1]		-	-	-	-	-	-
Sim. co-dependency direction[2]		-	-	-	-	-	-
Cross-MCI direction[3]		CP to S	Both	Both	-	CP to N	CP to S
Cross-MCI	SMOS	-0.2	-0.2	0.2	-	-	-0.2
	NDVI	-	-0.2	-0.2	-	-0.2	-
Cross-MCI lag*	SMOS	3	1	5	-	-	4
	NDVI	-	8	4.3	-	9	-

[1] Simultaneous non-linear co-dependency, [2] Direction refers to N= NDVI and S= SMOS

[3] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).

Table S4. Non-linear correlations and causality results for CP index, PCMCIPLUS method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.4	0.6	0.6	0.6	0.6	0.6
	NDVI	0.1	0.4	0.4	0.1	0.1	0.1
	CP	0.8	0.8	0.8	0.8	0.8	0.8
Sim. co-dependency[2] direction		-	-	-	Both	-	-
Sim. co-dependency[1]	SMOS	-	-	-	-0.2	-	-
	NDVI	-	-	-	0.2	-	-
Cross-MCI direction[3]		CP to S	-	-	-	-	CP to N
Cross-MCI	SMOS	-0.2	-	-	-	-	-
	NDVI	-	-	-	-	-	-0.1
Cross-MCI lag*	SMOS	3	-	-	-	-	-
	NDVI	-	-	-	-	-	1

[1] Simultaneous non-linear co-dependency, [2] Direction refers to N= NDVI and S= SMOS

[3] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).

Table S5. Non-linear correlations and causality results for EP index, ParrCorr method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.4	0.6	0.6	0.6	0.6	0.4
	NDVI	0.1	0.4	0.4	0.1	0.1	0.1
	CP	0.9	0.9	0.9	0.9	0.9	0.9
Sim. co-dependency[2] direction		-	-	-	-	-	EP to N
Sim. co-dependency[1]	SMOS	-	-	-	-	-	-
	NDVI	-	-	-	-	-	-0.2
Cross-MCI direction[3]		-	-	Both	EP to S	EP to S	-
Cross-MCI	SMOS	-	-	-0.2	-0.2	-0.2	-
	NDVI	-	-	-0.2	-	-	-
Cross-MCI lag*	SMOS	-	-	3	5	4.6	-
	NDVI	-	-	8	-		-

[1] Simultaneous non-linear co-dependency, [2] Direction refers to N= NDVI and S= SMOS

[3] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).

Table S6. Non-linear correlations and causality results for EP index, PCMCIPLUS method.

		CO	VE	WA	CA	SA	EA
Auto MCI	SMOS	0.4	0.4	0.6	0.6	0.6	0.6
	NDVI	0.2	0.2	0.2	0.1	0.1	0.1
	CP	0.9	0.9	0.9	0.9	0.9	0.9
Sim. co-dependency[2] direction		-	-	-	EP to N	-	-
Sim. co-dependency[1]	SMOS	-	-	-	-	-	-
	NDVI	-	-	-	-0.1	-	-
Cross-MCI direction[3]		-	-	-	EP to S	EP to N	-
Cross-MCI	SMOS	-	-	-	-0.2	-	-
	NDVI	-	-	-	-	0.2	-
Cross-MCI lag*	SMOS	-	-	-	5	-	-
	NDVI	-	-	-	-	3	-

[1] Simultaneous non-linear co-dependency, [2] Direction refers to N= NDVI and S= SMOS

[3] Cross-MCI lag refers to the lag between both series where a correlation is presented (measured in months).