Supplementary Information

Andean headwater and piedmont streams are hot spots of carbon dioxide and methane emissions in the Amazon basin

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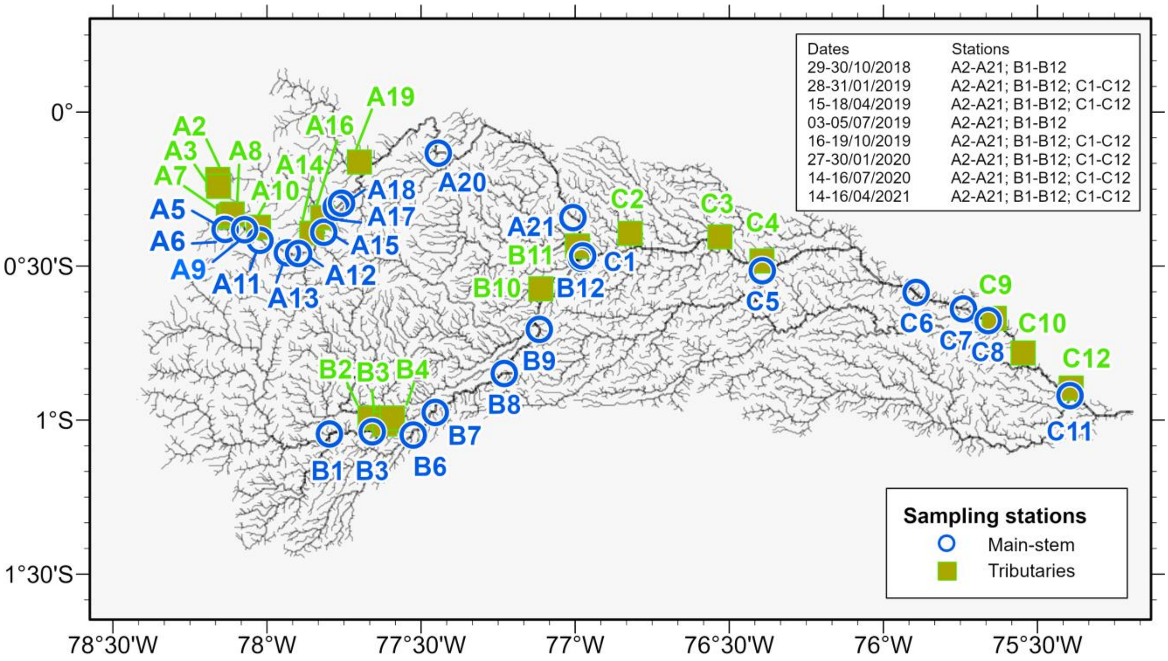
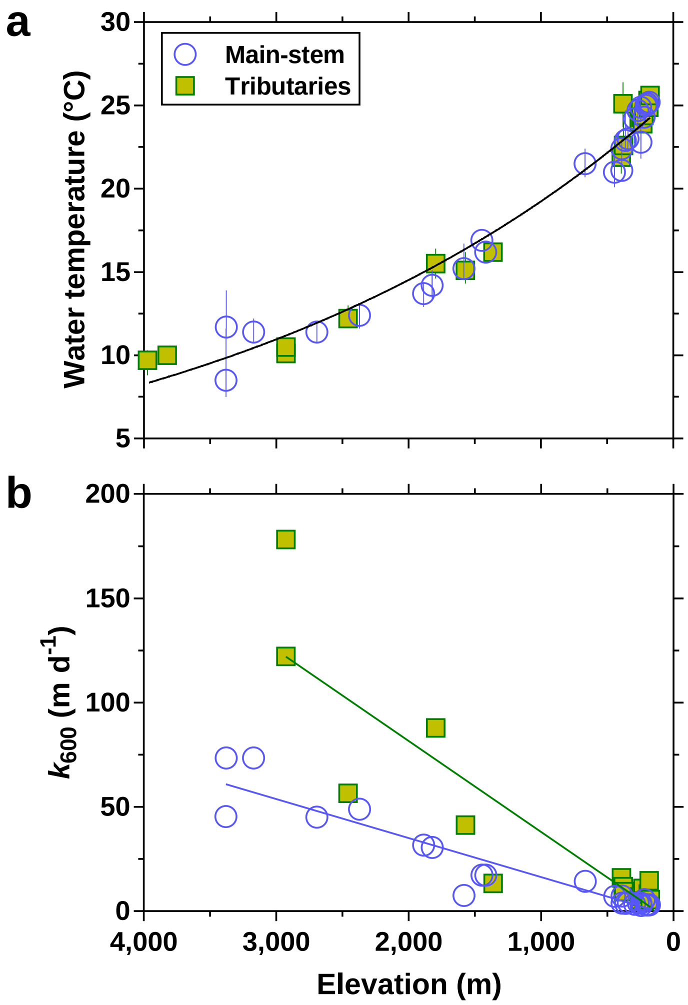
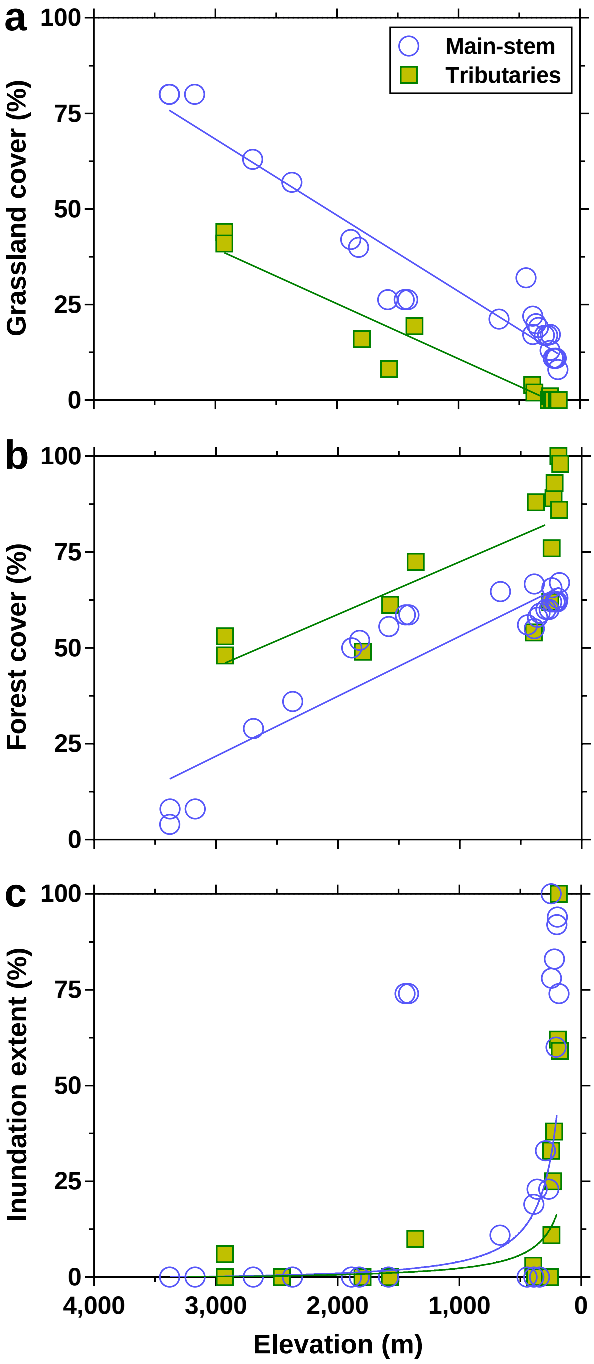
Supplementary Fig. 1 Location of stations in main-stem (blue circles) and tributaries (green squares) and sampling dates. Stations in the main-stem are shown by blue circles and in the tributaries by green squares.



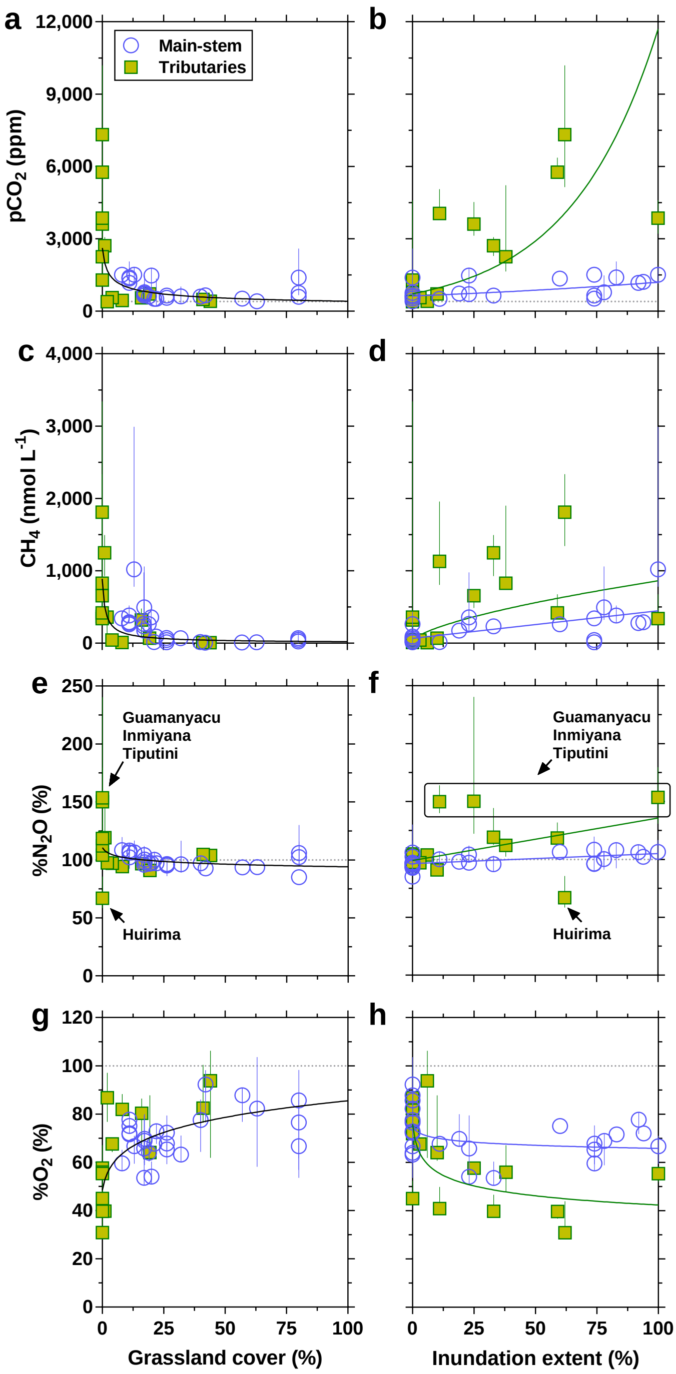
Supplementary Fig. 2 Strong elevation gradients of water temperature and gas transfer velocity in the Andean headwater and piedmont streams. Variations of measured water temperature (**a**) and the gas transfer velocity normalized to Schmidt number of 600 (k_{600}) modelled from freshwater discharge and stream gradient from RiverATLAS[68] (**b**) in the Napo streams as a function of elevation. Symbols show the median and error bars the interquartile range, stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4).



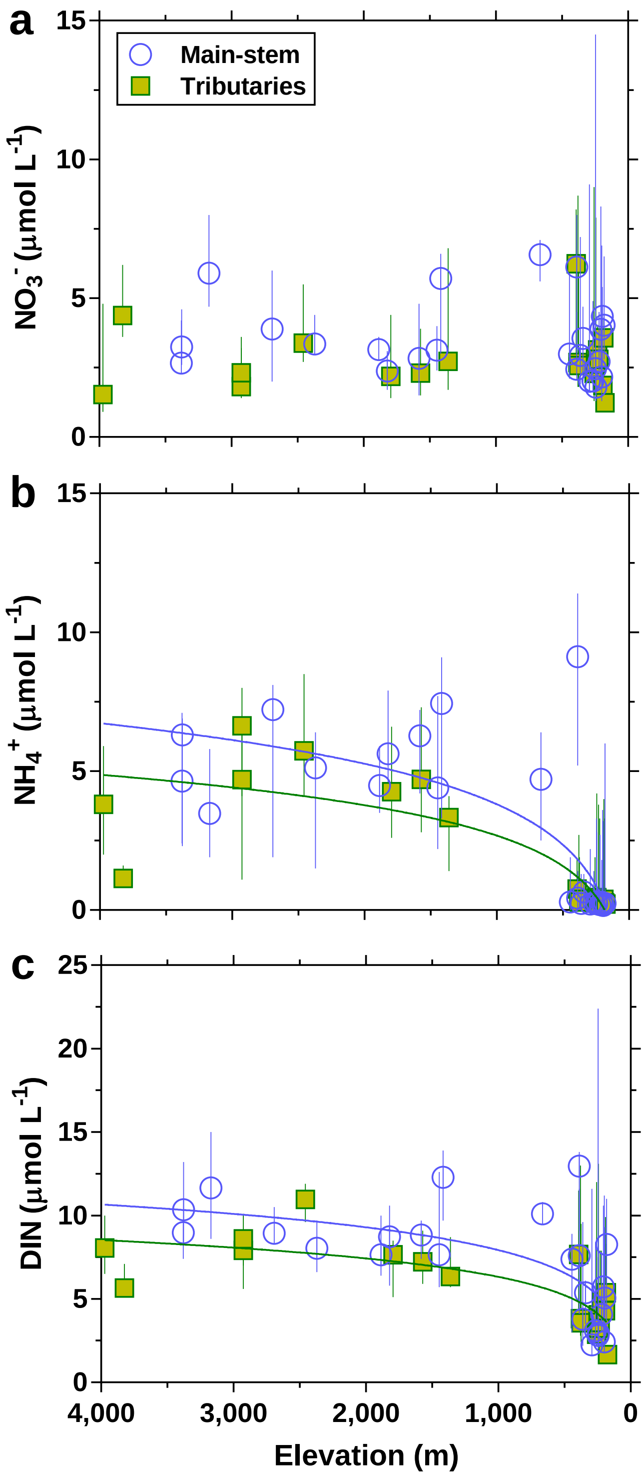
Supplementary Fig. 3 Strong elevation gradients of land cover in the catchment of Andean headwater and piedmont streams. Variations of grassland cover (**a**), forest cover (**b**) and inundation extent (**c**) in the Napo streams as a function of elevation, from Global Land Cover 2000 [115] and Global Inundation Extent from Multi-Satellites (GIEMS-D15)[18] extracted from RiverATLAS[68]. Grassland and forest cover are given over the total catchment upstream the sampled stream; inundation extent is given at the reach level. Stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4).



Supplementary Fig. 4 Grassland cover and inundation extent affect pCO_2, CH_4 and $\%N_2O$ in the Andean headwater and piedmont streams. Variations of the partial pressure of CO_2 (pCO_2), CH_4 dissolved concentration, N_2O saturation level ($\%N_2O$), and oxygen saturation level ($\%O_2$) in the Napo streams as a function of grassland cover (**a,c,e,g**) and inundation extent (**b,d,f,h**) in the Napo streams, from Global Land Cover 2000 [114] and Global Inundation Extent from Multi-Satellites (GIEMS-D15)[18] extracted from RiverATLAS[68]. Symbols show the median and error bars the interquartile range, stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4).

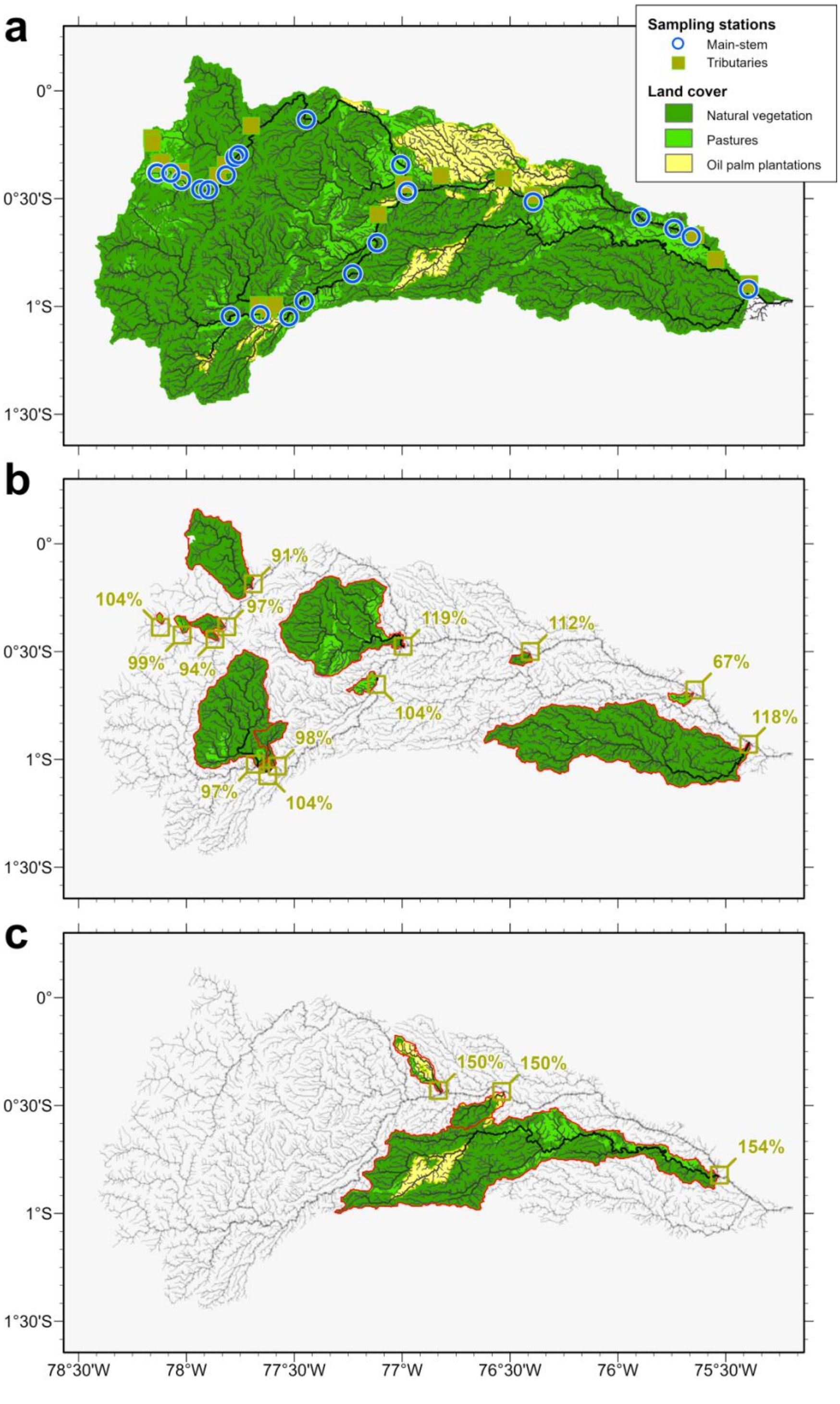


Supplementary Fig. 5 Elevation gradients of dissolved inorganic nitrogen in the Andean headwater and piedmont streams. Nitrate (NO_3^-), ammonia (NH_4^+) and dissolved inorganic nitrogen (DIN) concentration as a function of elevation in the Napo streams. Symbols show the median and error bars the interquartile range, stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4).

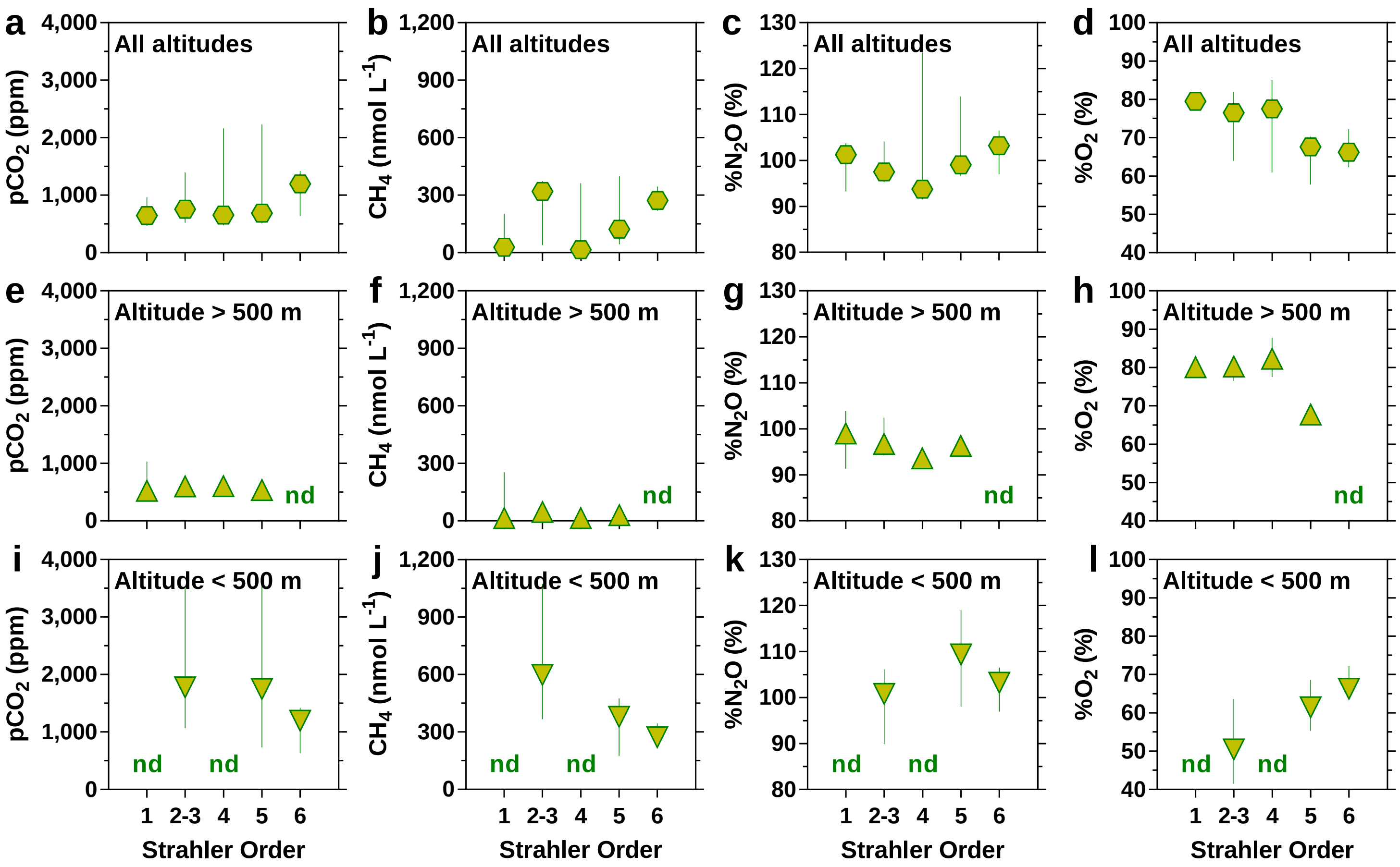


Supplementary Fig. 6 Aerial view of the Huirima stream showing meandering river course and presence of small lakes indicative of lateral inundation related to flat relief (low catchment slope). Landsat image was extracted from https://earthexplorer.usgs.gov/ and is in the U.S. Public Domain.

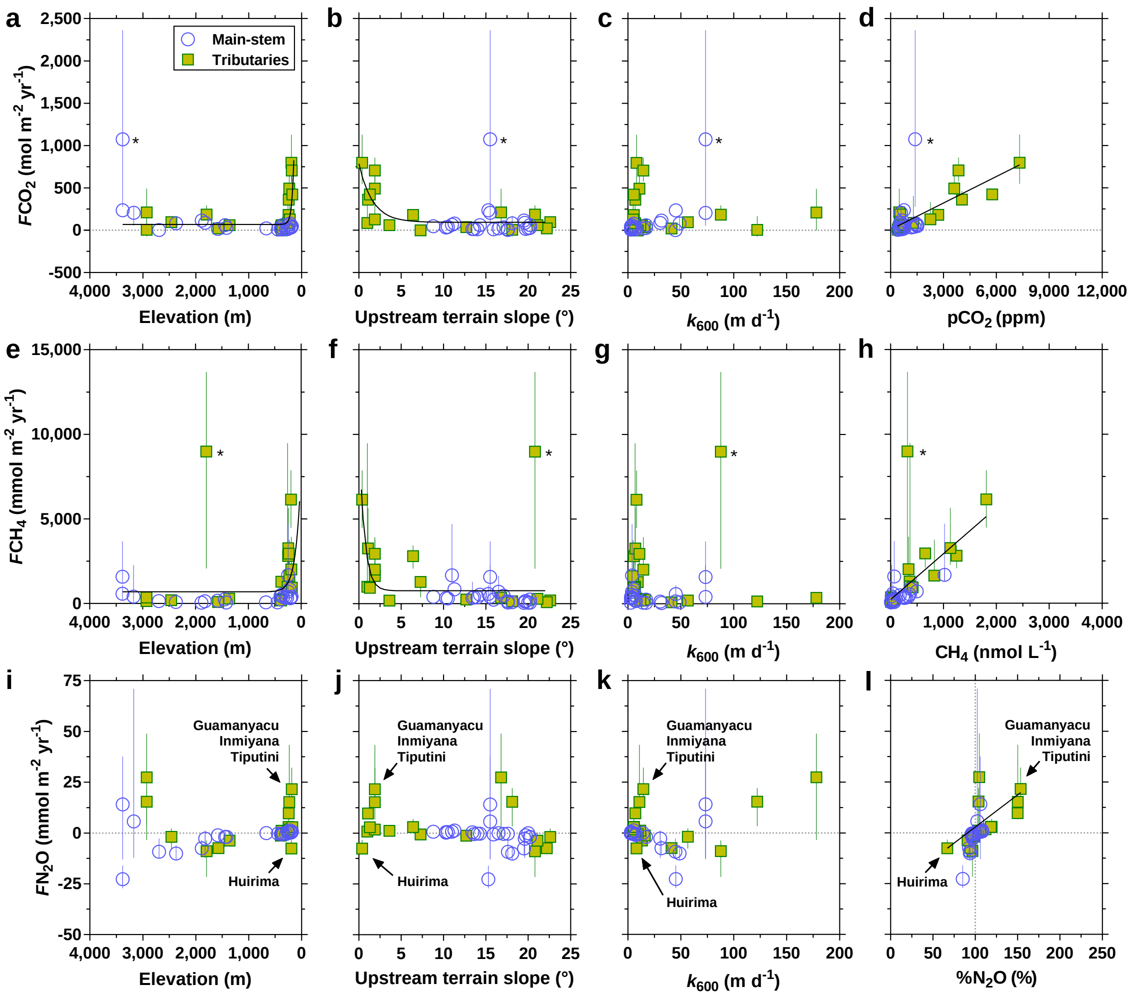
Supplementary Fig. 7 High N_2O levels are related to the presence of oil palm plantations in the Andean piedmont streams. Distribution of "natural" vegetation (merging forest and grassland) and agriculturally impacted land (pastures and oil palm plantations) in the Napo streams, for the whole catchment upstream of the most downstream station (**a**), and for individual catchments for N_2O saturation levels ≤ 119% (**b**) and ≥ 150% (**c**). Land covered by forest and grassland was merged into a single class (natural vegetation) by opposition to land cover strongly impacted by human activity (pastures and oil palm plantations). Stations in the main-stem are shown by blue circles and in the tributaries by green squares.



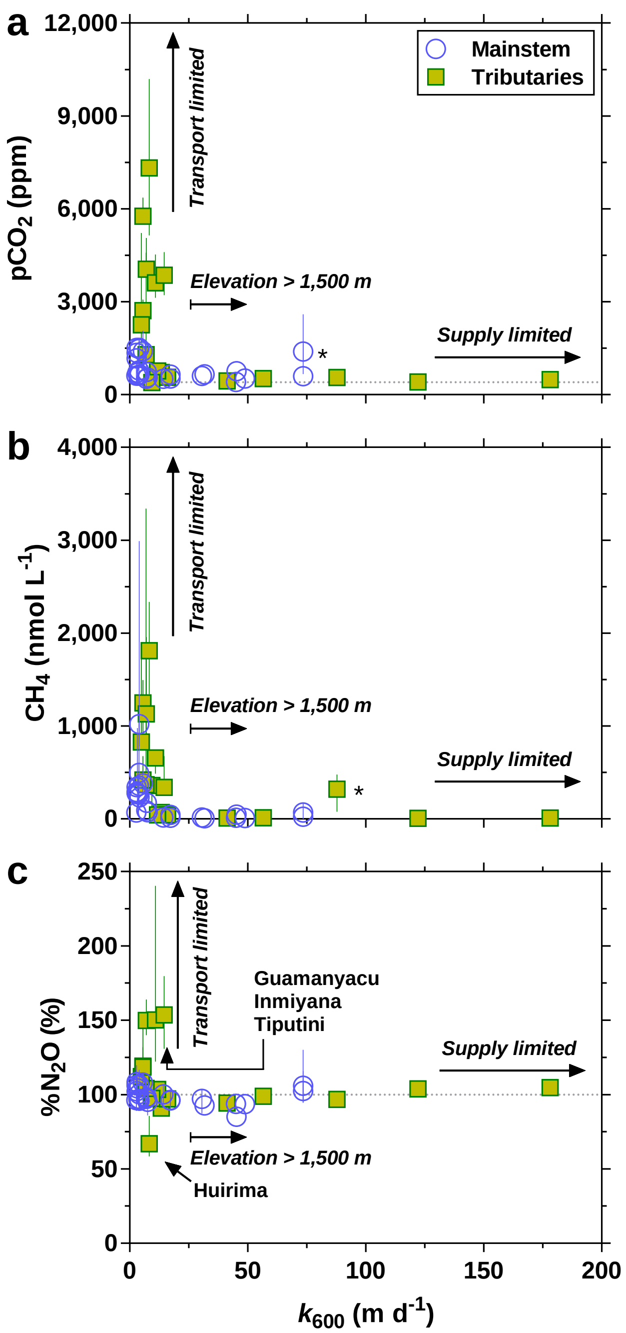
Supplementary Fig. 8 Low variations of pCO_2, CH_4 and $\%N_2O$ in the Andean headwater and piedmont streams as function of stream size. Variations of the partial pressure of CO_2 (pCO_2), CH_4 dissolved concentration, N_2O saturation level ($\%N_2O$), and oxygen saturation level ($\%O_2$) in the Napo streams as a function of Strahler order irrespective of elevation (**a,b,c,d**), for elevation > 500 m (**e,f,g,h**) and < 500 m (**i,j,k,l**). Due to low number of samples in low order streams, orders 2 and 3 were binned. Symbols show the median and error bars the interquartile range. nd = no data.



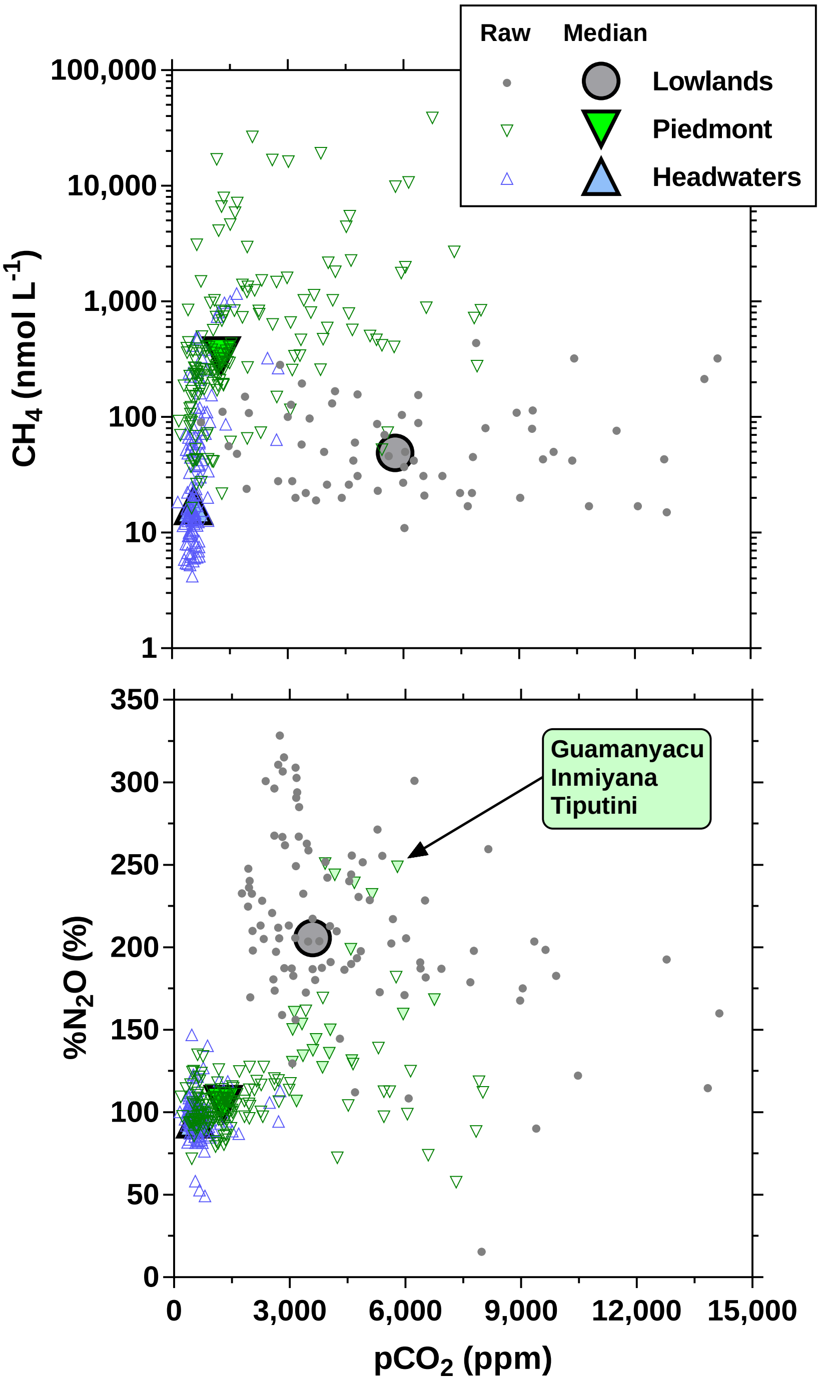
Supplementary Fig. 9 Strong elevation gradients of CO_2, CH_4 and N_2O emissions in the Andean headwater and piedmont streams. Air-water flux of CO_2 (FCO_2) (**a,b,c,d**), of CH_4 (FCH_4) (**e,f,g,h**) and of N_2O (FN_2O) (**i,j,k,l**) as a function of elevation (**a,e,i**), upstream terrain slope (**b,f,j**), gas transfer velocity normalized to Schmidt number of 600 (k_{600}) (**c,g,k**), and respective dissolved gas content: partial pressure of CO_2 (pCO_2) (**d**), CH_4 dissolved concentration (**h**), N_2O saturation level (%N_2O) (**l**). Symbols show the median and error bars the interquartile range, stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4). Asterisk indicates streams with high CO_2 and CH_4 concentrations and high k_{600} values (refer to Fig. S10).



Supplementary Fig. 10 Transport-limitation or supply-limitation of the gaseous exchange with the atmosphere in the Andean headwater and piedmont streams. Partial pressure of CO_2 (pCO_2) (**a**), CH_4 dissolved concentration (**b**), and N_2O saturation level (%N_2O) (**c**) as a function of the gas transfer velocity normalized to Schmidt number of 600 (k_{600}). Symbols show the median and error bars the interquartile range, stations in the main-stem are shown by blue circles and in the tributaries by green squares, and solid lines show fits to the data (Supplementary Table 4). Asterisk indicates streams with high CO_2 and CH_4 concentrations and high k_{600} values leading to comparatively higher emissions (refer to Fig. S9).



Supplementary Fig. 11 Strong elevation gradients of CO_2, CH_4 and N_2O in streams and rivers across the whole Amazon basin. Variations of CH_4 dissolved concentration (**a**) and N_2O saturation level (%N_2O) (**b**) as a function of the partial pressure of CO_2 (pCO_2). Data in the lowland rivers and streams was compiled extracted from plots of Richey *et al.*[34] with Plot Digitizer (http://plotdigitizer.sourceforge.net). Small symbols show individual measurements, large symbols indicate the median, the blue triangles show the data in the mountainous headwater streams, green triangles show the data in piedmont streams, and the grey circles show the data in the lowland streams and rivers.



Supplementary Table 1 Comparison of air-water fluxes of CO_2 (FCO_2) and CH_4 (FCH_4) in the Amazon rivers and streams from this study and reported in literature[5,16,27,30,31]. Only the diffusive component of FCH_4 is reported.

		FCO_2 mol m^{-2} yr^{-1}	FCH_4 mmol m^{-2} yr^{-1}
River channels < 150 m	**This study**	**161±11**	
	Reference [27]	156	
	Reference [5]	157	
River channels ≥ 150 m	**This study**	**91±6**	
	Reference [27]	71	
	Reference [5]	135	
Solimões/Amazon mainstem	**This study**		**66±29**
	Reference [30]		75
River channels ≥ 200 m	**This study**		**199±55**
	Reference [16]		274±41
River channels (whole lowland basin)	**This study**		**564±141**
	Reference [31]		370

Supplementary Table 2 Goodness of the linear regression of modelled partial pressure of CO_2 (pCO_2) based on three models versus observed pCO_2 from the Andean headwater and piedmont streams. The models were a linear regression (LR) as function of upstream slope, a multiple linear regression (MLR) as function of upstream slope and elevation, and a MLR as function of upstream slope and forest cover.

	Modelled pCO_2 versus initial pCO_2	r^2	*Sy.x*
Upstream slope LR	y = 1.284±(0.072) + 0.594(±0.023)*x	0.59	0.202
Upstream slope + Elevation MLR	y = 1.199(±0.071) + 0.620(±0.022)*x	0.62	0.200
Upstream slope + Forest cover MLR	y = 1.221(±0.071) + 0.613(±0.022)*x	0.61	0.200

Supplementary Table 3 Comparison of stream surface area in the Amazon basin used in this study (extracted from RiverATLAS[68]) and reported in literature[5,16,27,30,31]. The surface area for large lowland rivers used by Sawakuchi *et al.* [16] is two to three times higher than the range of values reported by Melack [27] for an equivalent river size class.

		Stream surface area km^2
River channels < 150 m	**This study**	**16,304 (*)**
	Reference [27]	31,000 (**)
	Reference [5]	27,120 (***)
River channels ≥ 150 m	**This study**	**21,668 (*)**
	Reference [27]	29,500 (**) to 52,000 (****)
	Reference [5]	25,500
Solimões/Amazon mainstem	**This study**	**4,994 (*)**
	Reference [30]	8,856
River channels ≥ 200 m	**This study**	**19,828 (*)**
	Reference [16]	91,212 (*****)
River channels (whole lowland basin)	**This study**	**40,375 (*)**
	Reference [31]	52,380 (******)

* Reference [68]
** Reference [115]
*** Reference [102]
**** from Shuttle Radar Topography Mission
***** Reference [116]
****** Unspecified data source

Supplementary Table 4 Equations and statistics at 0.05 level of curve fits of data shown in Figures.

Figure	Function	Equation	Average Residual	r^2	*p*	*n*
2 a	pCO_2 *versus* Elevation	*y* = 7.730E+04*EXP(-1.768E-02**x*)+6.623E+02	6.20E+02			44
2 b	pCO_2 *versus* Upstream terrain slope	*y* = 7.085E+03*EXP(-6.395E-01**x*)+8.108E+02	5.14E+02			42
2 c	pCO_2 *versus* Forest cover	*y* = 2.773E-02*EXP(1.229E-01**x*)+9.977E+02	5.56E+02			42
2 d	pCO_2 *versus* Water temperature	*y* = 6.775E-09*EXP(1.061E+00**x*)+3.882E+02	7.14E+02			42
2 e	CH_4 *versus* Elevation	*y* = 1.695E+03*EXP(-5.725E-03**x*)+9.183E+01	2.19E+02			44
2 f	CH_4 *versus* Upstream terrain slope	*y* = 1.202E+03*EXP(-6.150E-02**x*)-3.034E+02	1.71E+02			42
2 g	CH_4 *versus* Forest cover	*y* = 1.804E+01*EXP(4.134E-02**x*)-2.591E+00	1.83E+02			42
2 h	CH_4 *versus* Water temperature	*y* = 3.404E-02*EXP(3.844E-01**x*)+9.299E+01	2.29E+02			42
2 i	%N_2O *versus* Elevation	*y* = 7.940E+01*EXP(-9.046E-03**x*)+9.615E+01	4.05E+00			40*
2 j	%N_2O *versus* Upstream terrain slope	*y* = -0.8165**x* + 112.3		0.47	<0.0001	38*
2 k	%N_2O *versus* Forest cover	*y* = 0.1619**x* + 91.4		0.20	0.006	38*
2 l	%N_2O *versus* Water temperature	*y* = 9.648E-07*EXP(6.536E-01**x*)+9.610E+01	3.62E+00			38*
2 m	%O_2 *versus* log(Elevation)	*y* = 18.953**x* + 15.0		0.40	<0.0001	44
2 n	%O_2 *versus* Upstream terrain slope	*y* = 1.3564**x* + 50.1		0.40	<0.0001	42
2 o	%O_2 *versus* Forest cover	*y* = -0.3749**x* + 90.4		0.31	0.0002	42
2 p	%O_2 *versus* Water temperature	*y* = -1.5737**x* + 98.8		0.40	<0.0001	44
3 a	pCO_2 *versus* %O_2	*y* = 5.909E+04*EXP(-7.016E-02**x*)+4.755E+02	4.97E+02			44
3 b	pCO_2 *versus* CH_4	*y* = 0.2022**x* + 39		0.55	<0.0001	44
3 c	CH_4 *versus* %O_2	*y* = 1.863E+04*EXP(-7.885E-02**x*)+1.335E+02	4.97E+02			44
3 d	%N_2O *versus* pCO_2	*y* = 0.0053**x* + 94.8		0.46	<0.0001	40*
3 e	%N_2O *versus* %O_2	*y* = -0.2846**x* + 120.2		0.26	0.0009	40*
3 f	%N_2O *versus* DIN	*y* = -0.9479**x* + 106.5		0.15	0.0126	40*
4 a	log(pCO_2) *versus* log(Elevation)	*y* = -0.308**x* + 3.8443		0.50	<0.0001	403
4 b	log(pCO_2) *versus* log(Upstream terrain slope)	*y* = -0.6519**x* + 3.656		0.57	<0.0001	403
4 c	log(CH_4) *versus* log(Elevation)	$y = -0.1799*x^3 + 0.6348*x^2 - 0.1668*x + 1.7272$		0.40	<0.0001	471
4 d	log(CH_4) *versus* Upstream terrain slope (for Elevation > 180 m)	*y* = -0.0757**x* + 3.0622		0.42	<0.0001	297
4 d	log(CH_4) *versus* Upstream terrain slope (for Elevation < 180 m)	*y* = -0.1775**x* + 2.5974		0.21	<0.0001	174
4 e	log(CH_4:CO_2) *versus* log(Elevation)	$y = -0.2342*x^3 + 0.9761*x^2 - 0.5717*x - 3.1345$		0.44		369
4 f	log(CH_4:CO_2) *versus* Upstream terrain slope (for Elevation > 180 m)	*y* = -0.0489**x* - 1.8328		0.22	<0.0001	305
4 f	log(CH_4:CO_2) *versus* Upstream terrain slope (for Elevation < 180 m)	*y* = -0.1094**x* - 2.74		0.08	0.0239	64
S2 a	Water temperature *versus* log(Elevation)	*y* = -0.0001222**x* + 1.406		0.96	<0.0001	44
S2 b	k_{600} *versus* Elevation (for Main-stem)	*y* = 0.01869**x* - 2.266		0.89	<0.0001	25
S2 b	k_{600} *versus* Elevation (for Tributaries)	*y* = 0.0436**x* - 5.528		0.80	<0.0001	17
S3 a	Grassland cover *versus* Elevation (for Main-stem)	*y* = 0.01994**x* + 8.586		0.93	<0.0001	25
S3 a	Grassland cover *versus* Elevation (for Tributaries)	*y* = 0.01444**x* - 3.572		0.93	<0.0001	17
S3 b	Forest cover *versus* Elevation (for Main-stem)	*y* = -0.01556**x* + 68.6		0.85	<0.0001	25
S3 b	Forest cover *versus* Elevation (for Tributaries)	*y* = -0.01371**x* + 86.13		0.55	0.0025	17
S3 c	log(Inundation extent + 1) *versus* log(Elevation) (for Main-stem)	*y* = -1.333**x* + 4.702		0.49	0.0001	25
S3 c	log(Inundation extent + 1) *versus* log(Elevation) (for Tributaries)	*y* = -1.027**x* + 3.604		0.39	0.0078	17
S4 a	log(pCO_2) *versus* log(Grassland cover +1)	*y* = -0.4003**x* + 3.418		0.53	<0.0001	39
S4 b	Inundation extent *versus* log(pCO_2) (for Main-stem)	*y* = 0.002844**x* + 2.799		0.35	0.0017	25
S4 b	Inundation extent *versus* log(pCO_2) (for Tributaries)	*y* = 0.01206**x* + 2.858		0.61	0.0002	17
S4 c	log(CH_4) *versus* log(Grassland cover +1)	*y* = -0.8078**x* + 2.95		0.47	<0.0001	39
S4 d	log(CH_4) *versus* Inundation extent (for Main-stem)	*y* = 0.009493**x* + 1.635		0.34	0.0024	25
S4 d	log(CH_4) *versus* Inundation extent (for Tributaries)	*y* = 0.01461**x* + 1.879		0.27	0.0324	17
S4 e	log(%N_2O) *versus* log(Grassland cover +1)	*y* = -0.03509**x* + 2.044		0.35	0.0002	36*
S4 f	%N_2O *versus* Inundation extent (for Main-stem)	*y* = 0.08749**x* + 96.35		0.34	0.0022	25*
S4 f	%N_2O *versus* Inundation extent (for Tributaries)	*y* = 0.3674**x* + 98.98		0.64	0.001	13*
S4 g	log(%O_2) *versus* log(Grassland cover +1)	*y* = 0.123**x* + 1.685		0.49	<0.0001	39
S4 h	log(%O_2) *versus* log(Inundation extent+1) (for Main-stem)	*y* = -0.02816**x* + 1.875		0.19	0.0309	25
S4 h	log(%O_2) *versus* log(Inundation extent+1) (for Tributaries)	*y* = -0.1262**x* + 1.88		0.46	0.0027	17
S5 b	NH_4^+ cover *versus* Elevation (for Main-stem)	*y* = 2.104**x* - 10.73		0.57	<0.0001	25
S5 b	NH_4^+ cover *versus* Elevation (for Tributaries)	*y* = 1.58**x* - 8.237		0.71	<0.0001	17
S5 c	DIN cover *versus* Elevation (for Main-stem)	*y* = 1.989**x* - 5.851		0.45	0.0004	25
S5 c	DIN cover *versus* Elevation (for Tributaries)	*y* = 1.593**x* - 4.679		0.62	<0.0001	17
S9 a	*F*CO_2+2 *versus* Elevation	*y* = 3.858E+04*EXP(-2.674E-02**x*)+7.031E+01	1.05E+02			42
S9 b	*F*CO_2+2 *versus* Upstream terrain slope	*y* = 6.936E+02*EXP(-6.181E-01**x*)+9.523E+01	1.10E+02			42
S9 d	*F*CO_2 *versus* pCO2	*y* = 0.1045**x* + 6.451		0.45	<0.0001	42
S9 e	*F*CH_4 *versus* Elevation	*y* = 7.324E+03*EXP(-1.036E-02**x*)+6.882E+02	9.56E+02			42
S9 f	*F*CH_4 *versus* Upstream terrain slope	*y* = 9.751E+03*EXP(-1.635E+00**x*)+7.622E+02	8.02E+02			42
S9 h	*F*CH_4 *versus* CH_4	*y* = 2.711**x* + 217		0.38	<0.0001	42
S9 i	*F*N_2O *versus* N_2O	*y* = 0.316**x* - 28.72		0.13	0.0206	42

* Excluding Guamanyacu, Inmiyana, Tiputini, and Huirima Rivers

References

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