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Methane and nitrous oxide from Iberian inland waters: novel overall equations and a preliminary assessment of emissions

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ABSTRACT

Methane and nitrous oxide from Iberian inland waters: novel overall equations and a preliminary assessment of emissions

Estimations of gas emissions that impinge on global warming are growing worldwide as concern for this problem widens. Most are devoted to anthropogenic sources, but there is an increasing number dealing with natural sources. We offer here a preliminary assessment of methane and nitrous oxide emissions from Iberian freshwaters, mostly ascertained from reservoir data, which is probably the ecosystem type encompassing the higher fraction of inland aquatic cover in the Iberian Peninsula. Novel linear equations are produced using literature data and relating ecosystem area and annual emissions of CH_4 and N_2O at the ecosystem level. They enable us to estimate annual Iberian emissions of those gases which may be considered as a high limit because of many still unresolved uncertainties. Such equations could also be helpful to make estimations in other territories worldwide. Annual methane emissions by Iberian reservoirs would attain 19.45 Gg CH_4/y as a high extreme, that of nitrous oxide accounting for 0.43 Gg N_2O/y. As a result, Iberian reservoirs emit 541 Gg [CO_2-equivalent] per year of both gases together. The percentage of their inland water emissions is lower than 1 % of joint Portugal and Spain overall emissions in 2015. Interestingly, these estimations of methane and nitrous oxide emissions from freshwaters represent 71 % and 19 %, respectively, of non-anthropogenic emissions from Iberian Peninsula.

The obviously interesting topic of ascertaining CO_2 emissions by Iberian freshwaters is impaired by the fact of lacking data on the surface area of streams (which might be the main source on account of their more frequent heterotrophy) for the whole territory. Clearly, simple databases on Iberian inland waters (streams, wetlands, natural and man-made lakes, ponds…) including surface area, volume, depth and shape must be compiled to enable a more accurate description of their future changes, partly arising from global change. This morphometric database would also be very helpful to improve CH_4 and N_2O estimations.

Non-anthropogenic emissions from the Iberian Peninsula appear to be biased by IPCC estimation procedures, which are employed uncritically by Spanish and Portuguese governments. There is an urgent need to improve them regionally if the share of inland waters in gas emissions is to be accurately assessed.

Key words: greenhouse gases, non-anthropogenic emissions, ecosystem morphometry, troubles to assess overall CO_2 emissions

RESUMEN

Metano y óxido nitroso generado en las aguas continentales ibéricas: nuevas ecuaciones globales y estimación preliminar de emisiones

Las estimaciones de las emisiones de gases que afectan al calentamiento global están aumentando a medida que el problema se vuelve más serio en todo el mundo. La mayoría se dirige hacia las fuentes antropogénicas, pero hay una cifra en aumento que también considera a las fuentes naturales de dichos compuestos. Nosotros proporcionamos aquí una estimación preliminar de las emisiones de metano y óxido nitroso por los ecosistemas acuáticos continentales de la Península Ibérica, gran parte de las cuales son producidas por embalses, que es el tipo de ecosistema que ocupa la mayor superficie de las aguas interiores de la Península. En este artículo, aportamos nuevas ecuaciones que relacionan la emisión anual de ambos gases al nivel del ecosistema con la superficie de este, basadas en datos de la literatura, lo cual permite estimar una cifra que se halla en el

extremo superior de las emisiones anuales ibéricas, aunque todavía reste mucha incertidumbre. Dichas ecuaciones serían muy útiles para efectuar dichas estimaciones en otras partes del mundo. La emisión de metano en la Península alcanzaría un límite superior de 19.45 Gg CH_4/año, mientras que la debida al óxido nitroso sería de 0.43 Gg N_2O/año. Como resultado, los embalses ibéricos emitirían unos 541 Gg [CO_2-equivalente] al año de ambos gases. El porcentaje de esas emisiones supone menos del 1 % del total de las emisiones portuguesas y españolas en 2015. Sin embargo, dichas estimaciones representan el 71 % y el 19 %, respectivamente, de las emisiones no antropogénicas de metano y óxido nitroso en la Península Ibérica.
El tema obviamente interesante de la emisión del dióxido de carbono por los ambientes dulceacuícolas ibéricos se ve perjudicado por el hecho de la falta de datos sobre la superficie que ocupan los cauces fluviales en todo el territorio, pues esos ecosistemas serían los principales emisores del gas debido a su naturaleza predominantemente heterotrófica. Harían falta bases de datos sobre la morfometría de todos los ecosistemas acuáticos ibéricos continentales (embalses, ríos, humedales…), las cuales contemplen la superficie, el volumen, la profundidad y la forma del ecosistema, de manera que permitan una descripción más precisa de los efectos futuros sobre los mismos, parte de los cuales se deberán al cambio global. Esta base de datos morfométrica también redundaría en la mejora de las estimaciones de las emisiones globales de CO_2 y N_2O.
La cuantificación de las emisiones no antropogénicas de dichos gases por la Península Ibérica se halla sesgada debido a la metodología del IPCC, usada acríticamente por los gobiernos español y portugués. Habría que mejorarla urgentemente a nivel regional con objeto de poder establecer con precisión la contribución de su emisión generada por nuestras aguas continentales en comparación con los restantes tipos de emisión.

Palabras clave: *gases de efecto invernadero, emisiones naturales, morfometría de los ecosistemas, el problema de la determinación de las emisiones globales de CO_2*

INTRODUCTION

Carbon dioxide, methane and nitrous oxide are recognized as the main gases producing radiative forcing for global warming (i.e. greenhouse gases or GHG). The Intergovernmental Panel of Climate Change initiative (IPCC hereafter), but also individual countries like Portugal and Spain, has attempted to compute estimations of annual emissions, paying specific attention to anthropogenic emissions (IPCC, 2014; Agência Portuguesa do Ambiente, 2017; Subdirección General de Calidad del Aire y Medioambiente Industrial, 2017). Supranational and national entities implicitly assume that gas emissions from ecosystems are rather low as compared with those of human origin (i.e. industry, transportation, agriculture and livestock) and hence they happen to be negligible on a global basis (see references above). CO_2 evasion arising from land use, however, has entailed some 11 % of overall greenhouse emissions from the Biosphere in 2010 (IPCC, 2014).

Due to the fact that the percentage area covered by inland aquatic environments in the Iberian Peninsula is scarce, its contribution to GHG must be consequently low, but this cannot be an excuse to overlook it because the accuracy of emission assessments is mandatory at the country level by IPCC and it is certainly a goal to be improved. In addition, estimations of emissions could be useful for producing global estimates of ecosystem metabolism concerning carbon and nitrogen (Trimmer *et al.*, 2012), but they are usually neglected. Since methane and carbon dioxide emissions result from carbon metabolism, and that of N_2O derives from nitrogen metabolism, a good knowledge of those emissions would enable to fully complete carbon and nitrogen budgets in our inland aquatic environments, which is clearly a task for the future.

There are not many studies on GHG emissions from Iberian inland waters, but most deal with carbon dioxide (Sánchez-Andrés *et al.*, 2010; Alvarez Cobelas & Rojo, 2013; Ortiz Llorente, 2013; Morales-Pineda *et al.*, 2014; Gómez-Gener *et al.*, 2015, 2016; Alvarez Cobelas *et al.*, 2018; Obrador *et al.*, 2018), and only one is devoted to nitrous oxide (Castellano-Hinojosa *et al.*, 2017). This precludes their use as basic data to ascertain overall emissions for the whole territory. Global dioxide emissions and methane from inland waters have been reported by Raymond *et al.* (2013) and Bastviken *et al.* (2011), respectively, but we are not aware of such an effort for nitrous dioxide worldwide.

Estimates of GHG emissions from inland aquatic environments –which have been undertaken in other territories (Bastviken *et al.*, 2004;

Soued *et al.*, 2016)– have not been attempted for Portugal and Spain as yet. In the Iberian Peninsula, reservoirs encompass a good share of inland waters' cover. This does not dismiss the fact that other ecosystem types, such as streams, can also be sources of GHG (Raymond *et al.*, 2013), but they are unable to be used at present because of some limitations for reasons given below. Therefore, we have chosen to rely our estimates on data of Iberian reservoirs, their areal data being collected locally (http://cnpgb.apambiente.pt/gr_barragens/gbportugal; www.embalses.net).

Usually, the assessment of GHG emissions for large geographical areas uses data gathered at local sites which are extrapolated to wider areas after several statistical treatments (e.g. Bartlett & Harris, 1993; Bastviken *et al.*, 2004). As mentioned above, this approach cannot be employed for Iberian inland waters because the number of available data on true emissions is very low, if any as is the case for CH_4. In a first, preliminary approach to estimate GHG emissions from Iberian freshwater ecosystems we must rely on data sets gathered from larger Biosphere areas.

Regarding overall carbon dioxide emission from Iberian freshwaters, they cannot be estimated at present because we lack reliable data on a wide variety of issues: 1st) surface areas of Iberian streams; 2nd) surface areas of small lentic environments; 3rd) a better knowledge on emissions from stagnant waters as related to trophic status, which are usually related with CO_2 emission (Duarte & Prairie, 2005) and inorganic carbon inputs (Stets *et al.*, 2009; Marcé *et al.*, 2015); 4th) improved knowledge on the contribution by fluctuating ecosystem size and temporary terrestrial sites of inland waters (Harrison *et al.*, 2017; Obrador *et al.*, 2018). Furthermore, studies on CO_2 emission from streams are still very few (Gómez-Gener *et al.*, 2015, 2016) to be useful for regional estimations of emission.

Therefore, we have compiled data for CH_4 and N_2O emissions on an annual basis worldwide and the resulting equations relating ecosystem emission and area have been used to undertake a preliminary assessment of global emission from Iberian inland waters. We have restricted ourselves to reservoirs and some lakes in two districts (Pyrenees and Madrid County) and the estimated global values can be set as a high extreme of emissions from Iberian inland waters on several grounds: 1st) reservoirs encompass the larger overall area of freshwaters in Spain and Portugal, the remaining areas covered by wetlands, lakes and streams being surely much lower; 2nd) areal data of other ecosystems cannot be compiled easily for the whole Iberian Peninsula, 3rd) reservoirs are not always entirely filled up and hence their whole surface area is not always covered with water (i.e. their whole surface area does not function as a freshwater environment all the time and then our calculations cannot apply); 4th) streams are certainly sources of methane and nitrous oxide, but their quantitative contribution is far from being known. Thus, our estimations of methane and nitrous oxide emissions from Iberian reservoirs and those lake districts only are the single ones possible up to date. They are the first estimations of GHG emissions from Iberian inland waters in the second decade of the 21st century, but their improvement will certainly have to wait for better information concerning ecosystem areas and further, updated assessments of field emissions of GHG from Iberian inland waters.

MATERIAL AND METHODS

Broadly speaking, there have been two methods to tackle the problem of estimating global GHG emissions from individual, often scarce, data. The first one is based on gas emission measurements in a range of environments and later estimating the average areal emission times the whole surface area of ecosystems involved in the territory in case (see, for instance, Deemer *et al.*, 2016; Soued *et al.*, 2016). The second one is established through the linear relationship between ecosystem area and ecosystem emission (i.e. emission from the whole ecosystem; e.g. Bastviken *et al.*, 2004). We have chosen the latter approach since it appears to be more realistic because it considers variability of annual emissions as related with ecosystem area, instead of the emission average of the whole data set, and this could be more accurate for global estimations at the regional scale because the other method uses an average value for a hardly representative set of ecosystems. The main reason for this is the strong bias towards cold temperate environments, which have been far more studied than the remaining ones worldwide.

Data on annual worldwide emissions from freshwaters were taken from Ortiz-Llorente & Alvarez-Cobelas (2012) for methane and compiled for nitrous oxide from the literature (see below). All emission data were gathered along with areal data for each ecosystem. Data for methane include both ebullition and diffusion emissions collected worldwide; it is still uncertain what fraction of the whole emission is due to ebullition in reservoirs (see Deemers *et al.*, 2016 for a discussion), and hence a cautionary warning is in case. The number of data for CH_4 was high and increased using the relationship between emission in the most favourable date of the year and annual emission, reported by Ortiz-Llorente & Alvarez-Cobelas (2012, see their Table 3). This enabled us to perform a larger correlation analysis to increase robustness of the resulting relationship. We fit several models (linear, log, power, exponential, quadratic, polynomial and many more) to those data to obtain equations that enabled us to produce useful functions to estimate emissions at the ecosystem level depending upon ecosystem area. The goodness of fit of these procedures was ascertained using root mean square errors (RMSE hereafter). Two log-log equations for methane emission, one for wetlands and another for lakes (RMSEs = 0.793 and 0.873), were obtained (see Tables S1 and S2, supplementary information, available at http://www.limnetica.net/en/limnetica). The number of studies for annual N_2O emission from stagnant worldwide waters was much lower and we could only perform a pooled relationship for all ecosystem types; the lowest RMSE was also that of the log-log relationship (RMSE = 0.809) (see Table S3, supplementary information, available at http://www.limnetica.net/en/limnetica).

Therefore, linear log-log relationships were estimated between the area (m^2) of each environment and the annual emission of each gas from the whole ecosystem (g/ecosystem/year). 152 Portuguese and 660 Spanish reservoirs have been used for this approach (see Tables S4 and S5, supplementary information, which are available at http://www.limnetica.net/en/limnetica), accounting for 795 and 3138 km^2 of the surface area of each country, respectively. For methane, estimations on reservoirs have been split according to their average depth; if lower than 2 m, they were considered to behave as wetlands and the corresponding equation of Table 1 was applied; the remaining reservoirs were considered as lakes,

Table 1. Linear relationships between ecosystem area (m^2) and annual methane and nitrogen oxide emissions by diffusive processes in the whole aquatic ecosystem (g [CH_4 or N_2O]/ecosystem/y) for lakes and wetlands on a global basis. Methane data include both ebullition and diffusion emissions. For N_2O both data sets have been pooled together on account of their smaller size. Data have been Log10-transformed prior to estimations; therefore, base10-antilog calculation must be performed to know annual emissions for further environments where they have not been measured. See also Fig. 1. *Ecuaciones lineales entre la superficie del ecosistema (m^2) y las emisiones anuales de metano y óxido nitroso por el ecosistema acuático (g [CH_4 ó N_2O]/ecosistema/año) para lagos y humedales del mundo. Los datos de metano incluyen emisiones por difusión y ebullición. Para el óxido nitroso, ambos grupos de datos de partida se han fusionado debido a su menor número. Se ha realizado una transformación logarítmica en base 10 sobre los datos de partida; por lo tanto, debe llevarse a cabo el cálculo del antilogaritmo en base 10 del resultado de la ecuación para conocer las emisiones anuales en aquellos ambientes donde estas no se han medido directamente. Véase también la Figura 1.*

		Lakes (CH_4)	**Wetlands (CH_4)**	**Lakes and Wetlands (N_2O)**
N		104	89	27
Adjusted r^2		0.86	0.85	0.93
P		< 0.0001	< 0.0001	< 0.0001
Slope	Regression coefficient	1.15	0.88	1.01
	SE	0.05	0.04	0.05
Intercept	Intercept coefficient	-0.45	2.34	-0.97
	SE	0.31	0.35	0.29

using the corresponding equation of Table 1. The rationale basis for this splitting is two-fold: i) many small reservoirs have large shallow areas that behave as polymictic environments such as wetlands; and ii) 2 m as average depth of reservoirs is a conservative value which often implies max depths above 10 m (Alvarez Cobelas, unpublished data), thereby promoting lakes to stratify in the same way lakes do.

In addition, we have used data on Pyrenean

Table 2. Estimations of methane and nitrous oxide emissions by stagnant waters of conterminous Iberian Peninsula (i.e. excluding islands' environments), assuming that they are entirely filled up and using equations of Table 1. 95 % confidence ranges are shown in brackets and were ascertained by a bootstrap method (nr iterations: 9999). Estimations for Pyrenean lakes and Madrid gravel-pit lakes are also provided and were calculated using surface areas reported in del Castillo (2003) and Roblas & García Avilés (1997), respectively. Data on nationwide whole emissions are gathered from Agência Portuguesa do Ambiente (2017) and Subdirección General de Calidad del Aire y Medioambiente Industrial (2017) for Portugal and Spain, respectively. *Estimaciones de emisiones de metano y óxido nitroso por los ambientes acuáticos estancados de la Península Ibérica (excluyendo los situados en las islas), suponiendo que están llenos por completo y usando las ecuaciones de la Tabla 1. Se ha estimado un intervalo de confianza del 95 % mediante un método de "bootstrap" (número de iteraciones: 9999) y se muestra entre paréntesis. Se han hecho estimaciones también para algunas regiones lacustres españolas (lagos pirenaicos y lagunas de gravera de Madrid), usando las superficies lacustres referidas en del Castillo (2003) y Roblas & García Avilés (1997), respectivamente. Los datos de emisiones nacionales se han extraído de la Agência Portuguesa do Ambiente (2017) y de la Subdirección General de Calidad del Aire y Medioambiente Industrial (2017) para Portugal y España, respectivamente.*

	Extent (km^2)	CH_4 emission	Country CH_4 emission (%)	Non-anthropogenic CH_4 emission (%)	N_2O emission	Country N_2O emission (%)	Non-anthropogenic N_2O emission (%)
Portuguese reservoirs (Gg/year)	795	4.12 (4.96-6.23)	0.87	21	0.032 (0.007-0.047)	0.27	2.6
Spanish reservoirs (Gg/year)	3138	15.41(10.91-19.03)	0.92	207	0.402 (0.315-0.468)	0.72	37
Madrid gravel-pit lakes (Mg/year)	4	7.5 (2.7-10.6)			0.49 (0.25-0.67)		
Pyrenean lakes (Mg/year)	41	73 (62-82)			4.9 (4.3-5.4)		
Iberian Peninsula lentic waters (Gg/year)		19.55 (13.86-24.26)	0.91	71	0.43 (0.31-0.51)	0.64	19
Whole Portuguese emissions (Gg/year, 2015)		476			12		
Whole Spanish emissions (Gg/year, 2015)		1675			55		
Whole Iberian Peninsula emissions (Gg/year, 2015)		2151			67		
Portuguese non-anthropogenic emissions (Gg/year, 2015)		20			1.23		
Spanish non-anthropogenic emissions (Gg/year, 2015)		7.39			1.08		
Iberian non-anthropogenic emissions (Gg/year, 2015)		27.39			2.31		

lakes (del Castillo, 2003) and Madrid gravel-pit lakes (Roblas & García Avilés, 1997) to estimate CH_4 and N_2O emissions. Since we still lack easy-to-use data on areas of remaining Iberian stagnant and stream waters, we have had to restrict ourselves to those lakes and reservoirs.

A commonplace idea in ecology is that relationships between the whole and a part of it are spurious (Pearson, 1897). However, correlation between composite variables is legitimate if 1st) they conform to the assumptions of correlation analysis, 2nd) the variables represent concepts of interest and not merely a part of them, and 3rd) the variables do not share a large measurement error term (Prairie & Bird, 1989). These restrictions are fulfilled by our data since they meet assumptions of such an analysis, concepts are different (area *vs* ecosystem gas emission), and both variables do not share a large measurement error (error of ecosystem areal estimation is usually low). Furthermore, this procedure has been followed by Bastviken *et al.* (2004) in their estimation of regional and global estimates of methane emissions by freshwater environments.

We have also attempted to perform another estimation of GHG using the other approach (see above). Deemer *et al.* (2016) data base on methane emissions measured in reservoirs worldwide could be used as an average value to be multiplied by the overall surface of Iberian reservoirs. To tune this calculation further, we have only used data of reservoirs located within 36-44 º latitudes, which are those of Iberian Peninsula. This procedure would yield another estimation which could be compared with that of our approach. Unfortunately, only two data in Deemer *et al.* (2016) data set are available for nitrous oxide emissions from reservoirs of that latitudinal range, and hence they are not enough to use them in that manner.

Statistics were undertaken with the Statistica 7.0 package. In order to provide some range for uncertainty of our calculations, we estimated the 95 % confidence limits of the sums of emissions, using a bootstrap method supplied by the package Past 2.17 (Hammer *et al.*, 2001). Whole estimations for Iberian Peninsula were also reported as CO_2-equivalent units, the factors to compile them being reported in the fourth assessment of Climate Change (21 and 310 for methane and nitrous oxide, respectively, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html; Table 2.14). Although such factors may vary over time in the long-term, as suggested in that assessment, we have had no way to modify them accordingly and hence we used those factors which can be considered as very conservative.

RESULTS

Table 1 and Figure 1 report and depict relationships between ecosystem area and annual emission of CH_4 and N_2O for the whole ecosystem. They enabled us to estimate annual emissions and their ranges for Spanish and Portuguese reservoirs, and Pyrenean lakes and Madrid gravel-pit lakes as well, which were clearly much lower as expected from their whole surface areas, thus being almost negligible (Table 2). A high extreme of methane emissions by all those Iberian environments was 19.45 Gg CH_4/y (13.84-24.04 Gg CH_4/y), whereas that of nitrous oxide accounted for 0.43 Gg N_2O/y (0.34-0.50 Gg N_2O/y). Using the alternate approach by Deemer *et al.* (2016) of multiplying average emission values at 36-42 º latitudes from reservoirs times the overall area covered, this resulted in 61.78 Gg CH_4/y, and uncertainty was cumbersome and prevented to use their data for N_2O assessment (see above).

Using our approach, Iberian reservoirs emit some 541 Gg [CO_2-equivalent] per year of both gases. The percentage of freshwater emissions of both gases is then lower than 1 % of the whole emissions in 2015 for both countries (Table 2). However, when considering non-anthropogenic emissions the fractions encompassed by inland water emissions increased up to 71 % and 18 % for methane and nitrous oxide, respectively (Table 2). Surprisingly, our CH_4 estimation of freshwater emission exceeds that of all non-anthropogenic emissions from Iberian Peninsula, which is certainly puzzling.

DISCUSSION

CH_4 and N_2O emissions: accuracy, pitfalls and the future of estimations

Methane and nitrous oxide emissions from Iberian reservoirs are 1.1 and 0.9 %, respectively, of

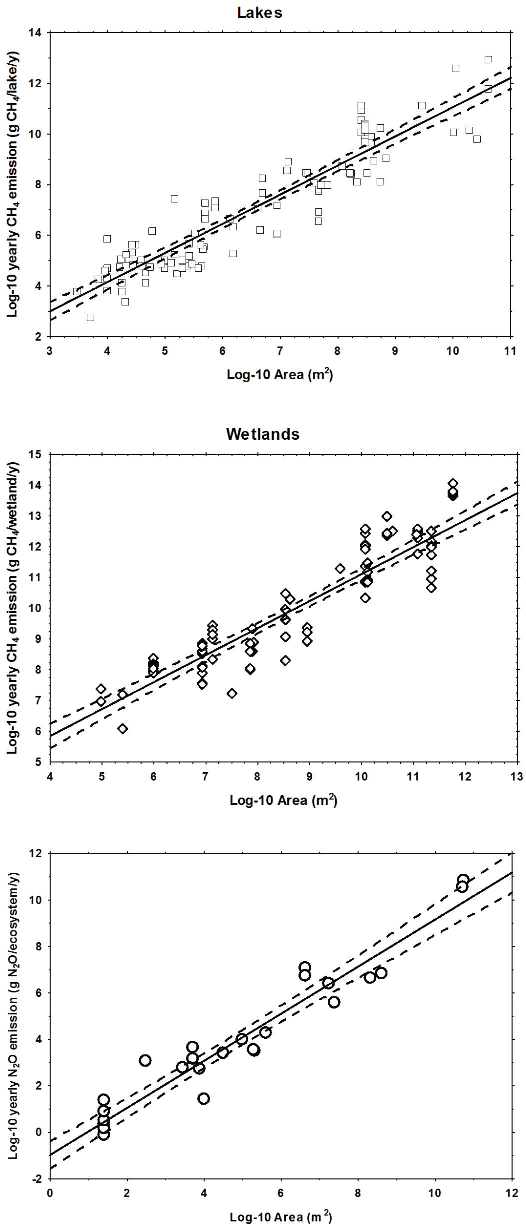

Figure 1. Log-log plots of ecosystem yearly emission vs ecosystem area for worldwide databases of CH_4 emission in lakes (upper panel) and wetlands (middle panel) and N_2O emission (lower panel) in all ecosystem types. Dashed lines indicate 95 % confidence limits. See Table 2 for equations and S1-S3 Tables for raw data. *Figuras logarítmicas de la relación entre emisiones anuales a nivel de ecosistema y superficie del mismo para las bases de datos de emisión de metano en lagos (panel superior), humedales (panel medio) y óxido nitroso (panel inferior), en este último caso para todos los tipos de ecosistema. Las líneas discontinuas representan los intervalos de confianza del 95 %. Véanse también la tabla 2 para conocer las ecuaciones de regresión y las tablas suplementarias S1-S3 para saber de dónde se han extraído los datos de partida.*

those from reservoirs worldwide (see Table 2 of this study and Table 1 by Deemer *et al.*, 2016). Despite the reported estimate for world reservoirs to emit 5.3 % of overall methane anthropogenic emissions (Deemer *et al.*, 2016; see their Table 1), Iberian reservoirs which may surely be the largest contributors to freshwater emission only outgas less than 1 % (Table 2). The reason for this is far from clear because the percentage area covered by reservoirs in the Iberian Peninsula is higher than that worldwide (0.7 % *vs* 0.06 %). Therefore, it is not surprising that the share of non-anthropogenic emissions of methane is higher in the latter where ruminant livestock, rice agriculture and biomass burning is far more important than in highly-developed countries like Portugal and Spain (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html). Regarding nitrous oxide, the situation is more even because its emission by worldwide reservoirs represents 0.43 % of all anthropogenic emissions of this gas, whereas it is 0.64 % in Iberian Peninsula (Table 2).

Our emission values from Iberian lentic waters could be considered to represent a high extreme of gas fluxes because the area covered by other inland waters is certainly much lower than that of reservoirs in Portugal and Spain plus both lake districts (Pyrenean lakes and Madrid gravel-pit lakes) whose emission estimations have been added to compute overall values. Anyway, there are more issues to be considered. The method of estimation of emissions is one of them. Deemer *et al.* (2016) use the product of bootstrapped estimates of averaged flux of methane for 75 reservoirs worldwide and the best estimates of reservoir area. When we used their approach, restricting ourselves to their data for reservoirs located at the same Iberian latitude, we reached a value that was some three-times higher than that estimated by our area-flux method (see above). In addition, Deemer *et al.* (2016) consider their estimation to be a low-end value of the range, also stating that emissions will increase in the future because of plans to increase the number of world reservoirs in the future. It is hard to suggest which approach is better at present, because both have their drawbacks (see the Material and Methods' section). Anyway, if theirs prove to be more suitable, our estimations would certainly increase by three-fold at least.

A finer tuning of lentic estimations must take water-level variations, and hence the effect on fluctuating water-covered surfaces, into account, but also parts of reservoir functioning as either a stratified lake or a polymictic lake would be worth considering (i.e. deep and shallow areas) because it has been shown that shallow lakes outgas more methane than deep lakes (Ortiz-Llorente & Alvarez Cobelas, 2012), and this might also occur for nitrous oxide. To improve those estimations ecosystem geometry (Michels, 1977; Carpenter, 1983) and processes of water drawdown must be considered as well because there is some evidence that they could increase CH_4 emissions (Harrison *et al.*, 2017), and this could also affect other gases. It is also certain that spatial heterogeneity of emissions in large environments, like those of Alqueva (Portugal), Mequinenza and La Serena (Spain) reservoirs, is hard to be assessed. In fact, there are very few instances of emission measurements worldwide in more than ten sites of a single reservoir (Deemer *et al.*, 2016), but these authors suggest that inlets and shallow areas can be of overwhelming importance for the highly spatially-variable CH_4 emissions from the whole environment.

Anyway, it is hard to know at present whether these further improvements of methodology might increase or decrease estimations because some effects (e.g. drawdown increase) counteract others (e.g. low water availability arising from low rainfall).

Other features must also be taken into account if these emission values are to be improved in the future. Dry areas of inland waters (i.e. temporary environments, including dry areas of reservoirs) also emit methane because they behave as soils (Jin *et al.*, 2016). Furthermore, seasonal variability of emissions could be meaningful because CH_4 and N_2O peaks usually occur during late Spring and in Summertime (Ortiz-Llorente & Alvarez Cobelas, 2012; Hefting *et al.*, 2003; Soosar *et al.*, 2011). Stratifying environments of high trophic status are also responsible for outgassing those substances, which are mostly produced at anoxic hotspots of hypolimnion and sediments. Since stratification length is suggested to increase along with global warming (Adrian *et al.*, 2009), it is expected that emissions of those gases will increase in the decades to come. In fact, there is some evidence that stratification has increased at the rate of 18 days/decade in a Madrid nearby lake (Las Madres, Benavent, 2015). The situation is also likely to be important because most Iberian reservoirs are reported to be eutrophic or hypertrophic (Alvarez Cobelas *et al.*, 1992; Vieira *et al.*, 2013), thus enhancing methane and nitrous oxide production.

Regarding nitrous oxide emissions, a further feature must be discussed. Some N-poor, eutrophic environments (e.g. shallow stagnant waterbodies and streams in non-agricultural areas) can behave as sinks for this gas due to its consumption in sediments resulting from reduced conditions, and hence their annual emission can be negative (Soued *et al.*, 2016). This would complicate estimations of N_2O outgassing at the regional scale, as is the case for the Iberian Peninsula.

Anyway, our preliminary estimations suggest that gas emissions from freshwaters encompassed a good fraction of non-anthropogenic emissions in the Iberian Peninsula (Table 2) and hence they must be considered if a more accurate balance of global warming gases is pursued. Clearly, this non-anthropogenic emission deserves closer scrutiny and needs an improved estimation (see below) regarding the extant ones (Agência Portuguesa do Ambiente, 2017; Subdirección General de Calidad del Aire y Medioambiente Industrial, 2017).

To provide researchers and environmental managers with a more accurate estimation of emissions, we Iberians need to improve our areal data of all inland water environments. At present their morphometric datasets are not compiled for all ecosystem types, which preclude any further estimations. A recent, very valuable effort in that way is that of Pekel *et al.* (2016) on a worldwide basis, but it still needs to be developed at regional scales to be fully operative and usable for country purposes because it has two drawbacks to use it straightforwardly: 1st) the database is a GIS-based feature where aquatic environments are not classified by typologies (i.e. rivers cannot be viewed as different from stagnant waters); and 2nd) its spatial resolution

(36x36 m) is certainly great, but it does not enable to consider smaller environments, largely important for biogeochemical processes (Downing, 2010), whose number is very high in the semi-arid Iberian Peninsula. Otherwise, estimations of global warming effects, such as water regime changes (e.g. permanent to temporary), their decreasing numbers arising from lower water availability linked to decreasing rainfall and increasing human consumption, changes in biogeochemical fluxes and so on (Álvarez-Cobelas *et al.*, 2005) will be hard to be assessed for our inland waters.

The problem of assessing overall CO_2 emission from Iberian inland waters

In addition to the trouble caused by lacking surface areas of Iberian streams, mentioned earlier, we also lack data enough on CO_2 evasion from streams, most of which arises from ecosystem respiration (Izagirre *et al.*, 2008; Wallin *et al.*, 2013). Studies on CO_2 outgassing from Iberian streams are still very few (Gómez-Gener *et al.*, 2015, 2016) to sustain a similar approach to that of Deemer *et al.* (2016). However, oxygen and temperature data gathered from continuous records for many Iberian streams are available (www.snirh.apambiente.pt; www.sig.mapama.es/redes-seguimiento) with enough temporal resolution (minutes) to permit ecosystem respiration estimations even at the yearly scale. Such data, along with estimations of the reareation coefficient (McBride, 2002), would enable to estimate respiration on an areal basis to produce similar equations to those of Table 1 that could be used jointly with areal data of Iberian rivers to produce an estimate of CO_2 emission from Iberian inland water environments. The use of Pekel *et al.* (2016) data to compile areal data for Iberian rivers will enable to perform estimations of CO_2 evasion from streams in due time.

Concerning lentic waters, it has recently been reported that dry areas of temporary environments are sites of high CO_2 emission and hence they must be included in future assessments (Obrador *et al.*, 2018), providing that areal data are available for most of them in order to reach a sound value.

GHG emissions from inland waters and overall sources from the Iberian Peninsula

This preliminary study reveals that inland waters are causing a good share of CH_4 and N_2O of non-anthropogenic emissions (Table 2). Sometimes they can exceed them (being twice the official value of non-anthropogenic emission), as is the case for methane, a fact that could point to the inaccurate estimation of the latter. It is not likely that our values would be underestimated due to the reasons outlined above, and because we have neglected to add CH_4 emissions from streams due to the lacking of sound ways of estimation.

Estimations of non-anthropogenic emissions by Portuguese and Spanish governments (Agência Portuguesa do Ambiente, 2017; Subdirección General de Calidad del Aire y Medioambiente Industrial, 2017) rely on guidelines of 2006 IPCC (https://www.ipcc-nggip.iges.or.jp/public/2006gl), but they are poorly accurate and very often than not they have used default values. Furthermore, some issues –such as wetlands or crops other than rice in the Spanish report, and field burning of agricultural residues and urea application in the Portuguese one– are not even reported. It is time to develop better methods to quantify non-anthropogenic emissions, which must certainly have to be region-specific. This is clearly a task for the future, but cannot be overlooked if we are to have more accurate non-anthropogenic GHG emissions against which to compare ecosystem emissions.

CONCLUDING REMARKS

This exercise has enabled us to produce i) novel gas emission-area relationships, and ii) the first estimations of methane and nitrous oxide gas emissions from Iberian inland waters, which are certainly important as compared with the remaining non-anthropogenic emissions. They are also useful to provide insights in global C and N metabolism of these environments (see, for instance, Alvarez-Cobelas & Sánchez-Carrillo, 2016), an often neglected task for freshwater on account of their incorrectly suspected lack of significance on a global scale (but see Cole *et al.*, 2007).

To improve CH_4 and N_2O estimations and their accuracy, and CO_2 emission' estimations as well, there is an urgent need to compile the best dataset on simple features of Iberian inland waters, such as number of ecosystems, surface area, maximum volume and depth, water-level variations and so on. This task could be performed using the study by Pekel *et al.* (2016) and their accompanying information as a basis. Such efforts will surely result in much better estimations of non-anthropogenic contributions to radiative forcing in the Iberian Peninsula, but they must proceed along with better estimations of all non-anthropogenic emissions from our countries.

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