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Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data

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Abstract

Many recent reviews and meta-analyses of N_2O emissions do not include data from Mediterranean studies. In this paper we present a meta-analysis of the N_2O emissions from Mediterranean cropping systems, and propose a more robust and reliable regional emission factor (EF) for N_2O, distinguishing the effects of water management, crop type, and fertilizer management. The average overall EF for Mediterranean agriculture (EF_{Med}) is 0.5%, which is substantially lower than the IPCC default value of 1%. Soil properties had no significant effect on EFs for N_2O. Increasing the nitrogen fertilizer rate led to higher EFs; when N was applied at rates greater than 400 kg N ha^{-1}, the EF did not significantly differ from the 1% default value (EF: 0.82%). Liquid slurries led to emissions that did not significantly differ from 1%; the other fertilizer types were lower than 1% but did not significantly differ from each other. Rain-fed crops in Mediterranean regions have lower EFs (EF: 0.27%) than irrigated crops (EF: 0.63%). Drip irrigation systems (EF: 0.51%) had 44% lower EF than sprinkler irrigation methods (EF: 0.91%). Extensive crops, such as winter cereals (wheat, oat and barley), had lower EFs (EF: 0.26%) than intensive crops such as maize (EF: 0.83%). For flooded rice, the inundated environment favored anaerobic conditions leading to complete denitrification and low EFs (EF: 0.19%). Our results indicate that N_2O emissions from Mediterranean agriculture are overestimated in current national greenhouse gas inventories and that, with the new EF determined from this study, the effect of mitigation strategies such as drip irrigation or the use of nitrification inhibitors, even if highly significant, may be smaller in absolute terms.

Keywords: N_2O, greenhouse gases, field studies, mitigation, systematic review

1. Introduction

More than half of the global Mediterranean climate zone is located on the Mediterranean Sea Basin (Aschmann, 1973); the remainder is on the Pacific coast of North America, south-western Australia, the Cape region of South Africa and the central coast of Chile (Olson et al., 2001). One of the most distinctive features of Mediterranean climates is the summer drought and relatively mild temperatures in winter. However, annual precipitation is variable, between 275 and 1000 mm, such that Mediterranean climate regions range from semi-arid to humid.

In Mediterranean climates, precipitation and temperatures are suitable in winter for cultivating a variety of rain-fed crops including cereals, grain legumes, and oilseeds. Horticulture is also an important component of Mediterranean farming (Andrews et al., 2002). A typical characteristic of the Mediterranean climate zone is the cultivation of perennial crops, some of which are resistant to summer droughts, including olives, almonds, and grapes, while others are cultivated under irrigation, such as citrus and other fruit trees. Agriculture in Mediterranean climates regions, therefore, provides a high diversity of crops.

Agricultural soils are regarded as the primary source of anthropogenic N_2O emissions (Smith et al., 2008). Despite the cultural and economic importance of Mediterranean agriculture (Grigg, 1974), the number of field studies analyzing N_2O emissions from Mediterranean agricultural lands is much smaller than from other temperate areas (Stehfest and Bouwman, 2006). Recent reviews and meta-analyses of N_2O emissions do not include data from Mediterranean studies (e.g. Kim et al., 2013; Lesschen et al., 2011; Shcherbak et al., 2014). Estimating N_2O emissions and N_2O emission factors (EF, the percentage of fertilizer N applied that is transformed and emitted on site as N_2O once the soil contribution has been discounted) is essential for assessing the impact of agriculture on greenhouse gas (GHG) emissions for a particular area. Current national emission inventory methods use a direct EF for N_2O, with a default value of 1% or 1.25% (depending on the country) of the N input from manure and mineral fertilizer (IPCC, 2006). However, many studies have concluded that the response of direct N_2O emissions to N input is non-linear (Kim et al., 2013; Philibert et al., 2012; Shcherbak et al., 2014), and other recent studies highlighted the important role of environmental and management factors in determining N_2O emissions and EFs, such as climate, soil characteristics, type of fertilizer and time of application, crop type, and irrigation system (Aguilera et al., 2013a; Bouwman et al., 2002; Gerber et al., 2016; Leip et al., 2011; Lesschen et al., 2011). For example, Aguilera et al. (2013a) suggested using a lower EF for Mediterranean crops than for other temperate crops, especially in rain-fed systems.

There are three characteristics of Mediterranean regions that are fundamental to understanding why soil N_2O emissions from these regions are idiosyncratic and in-turn why the adoption of EFs which differ from other climate regions should be considered. Firstly, the typical seasonality in Mediterranean agroecosystems means that irrigation is a prerequisite for the cultivation of many annual crops during summer, whereas mild, humid winters enable annual crops to be rain-fed. Different EFs are therefore needed for irrigated and rain-fed crops. Secondly, soils in the Mediterranean zone generally have a neutral to alkaline soil pH and very low concentrations of organic C (Aguilera et al., 2013b; Verheye and de la Rosa, 2005). These conditions influence denitrification rates and N_2O/N_2 ratios (Li et al., 2005; Šimeck and Cooper, 2002). Thirdly, soils in Mediterranean regions are rarely exposed to freeze–thaw cycles, which cause high N_2O emissions, especially in fertilized soils (Schouten et al., 2012; Tenuta and Sparling, 2011), which lead to high EFs.

The aim of this study was to improve our understanding of soil N_2O emissions from Mediterranean cropping systems by (i) conducting a meta-analysis of soil N_2O emissions; (ii) proposing a more robust and reliable regional EF; and (iii) identifying controlling factors of N_2O EFs (soil type, climate variability, irrigation and N fertilizer management) as a basis for developing soil N_2O mitigation strategies for regions with Mediterranean climates.

2. Methods

2.1. Selection of studies and data extraction

There are varying definitions to demarcate Mediterranean climate regions worldwide, which are typically based on climate and plant associations. We chose the widely used delineation of the Mediterranean biome from the collection of ecoregions mapped by the World Wildlife Fund (Fig. 1). We selected studies within this area and studies in marginal areas that were defined by authors as ‘Mediterranean’ in the original papers. Soil N_2O data from field-based studies investigating fertilizer-induced soil N_2O emissions were collected from these Mediterranean regions, including the Mediterranean Sea Basin, California, Australia and Chile (Fig. 1). We are not aware of any field study reporting N_2O emissions in the Mediterranean region of South Africa (Mary Scholes, Wits University, personal communication).

The criteria for inclusion of a study in the dataset were: (i) area-scaled N_2O emissions were reported for N fertilizer treatments, (ii) the number of replicates was reported unambiguously with a minimum of three replicates per treatment, and (iii) only field studies were considered and only when N_2O emissions were reported for at least an entire growing season.

The cumulative N_2O emissions for each N fertilizer treatment were extracted from published papers and reports, together with a measure of variance, the number of replicates and the N application rate (kg N ha^{-1}) for the experimental duration. Key characteristics (location, climatee data, soil type, soil management, irrigation, type of fertilizers, etc.) were collected when available (Supplementary Material 1 presents the complete dataset used in the analysis). When data were presented graphically, *WebPlot Digitizer* was used to extract data points (http://arohatgi.info/WebPlotDigitizer/). If cumulative N_2O emissions or other information were not reported, the authors of the field study were contacted to supply missing information. In some cases, cumulative emissions were estimated by integrating the average daily fluxes over the measurement period (Alluvione et al., 2010; Castaldi et al., 2011; Kong et al., 2009; Ranucci et al., 2011; Vitale et al., 2013). Experiments assessing the effect of nitrification/urease inhibitors were studied as a separate group (when evaluating the influence of the type of fertilization), but were not included to obtain the mean EF for Mediterranean crops (EF_{Med}) because they were not considered representative of current management practices. Fifty-three studies and 223 datasets were included in the meta-analyses (Table 1, Supplementary Material 1).

Since most of the field studies in our database focus on assessing the performance of specific crop management practices over both emissions and crop yields, they often do not include post-harvest season emissions. While full year emissions are desirable for determining EFs (IPCC, 2016), in the systems we are studying, we assume that the inclusion of growing season only emissions will have minimal influence on our calculated EFs, since emissions in the intercrop period will be a) low in summer (fallow of winter crops), when the soil is dry, due to decreased microbiological activity, and b) very low in winter (fallow of summer crops) under cold conditions without freeze–thaw cycles (Aguilera et al., 2013a). In the few studies where emissions were measured over an entire year, those during the fallow period were 10% or less of the total (Sanz-Cobena et al., 2012).

2.2. Soil and land management data compilation

Soil and land management data was grouped into categories based on soil pH_{H2O}: (i) pH<7.5 and (ii) pH>7.5; soil texture: (i) coarse (sandy loam, sandy clay loam, loamy sand), (ii) medium (clay loam, loam, silty clay loam, silt, silt loam), and (iii) fine (clay, silt clay, sandy clay) (USDA, 1999); soil organic C concentration: low (<10 g C kg^{-1} soil), medium (10–20 g C kg^{-1} soil), and high (>20 g C kg^{-1} soil); water input and management: (i) rain-fed and annual precipitation <450 mm, (ii) rain-fed and annual precipitation >450 mm, (iii) sprinklers, (iv) flooded, (v) furrow or surface irrigation, and (vi) drip irrigation; type of N fertilizer: (i) synthetic (including all types of mineral fertilizers), (ii) organic-solid (compost, solid fraction of manures, solid organic residues), (iii) organic-liquid (pig/cattle slurries, liquid fraction of slurries, digestates), (iv) organic-synthetic mixture, and (v) inhibitors (nitrification and/or urease inhibitors: DCD, DMPP,NBPT); N fertilizer rate: (i) <100 kg N ha^{-1}, (ii) 100–400 kg N ha^{-1}, and (iii) >400 kg N ha^{-1}; type of crop: (i) winter cereals (hereafter: 'cereals'), (ii) horticulture, (iii) maize, (iv) rice, (v) perennials, and (vi) other. The soil pH values measured with $CaCl_2$ were converted to values measured in distilled water using a method described by Minasny et al. (2011).

2.3. Calculation of emission factors

Most studies included in the meta-analysis did not explicitly report EFs since they were designed with different aims, e.g. analyzing the impact of different irrigation systems (Kennedy et al., 2013; Sánchez-Martín et al., 2008), soil management (Plaza-Bonilla et al., 2014), rate or type of fertilizers (Sánchez-García et al., 2016) or the impact of nitrification inhibitors (Huérfano et al., 2015) on soil N_2O emissions. We calculated EFs as the difference between N_2O emissions from a fertilized treatment (kg N_2O-N ha^{-1}) and the non-fertilized (control) treatment (kg N_2O-N-N ha^{-1}) divided by applied N fertilizer (kg N ha^{-1}). In 39% of cases, there was no control treatment and these missing data were obtained through multiple imputation by chained equations (Azur et al., 2011) with IBM SPSS Statistics 24 (for a detailed description of missing data treatment and sensitivity tests see Supplementary Material 2).

2.4. Data analysis

We performed a standard pair-wise meta-analysis using emission factors (EFs) as effect sizes with MetaWin version 2 (Rosenberg et al., 2000). Mean effect sizes for each grouping and the 95% confidence intervals (CI) generated by bootstrapping (999 iterations) were calculated using a categorical random effects model (Adams et al., 1997). For a detailed description of the statistical procedure see Supplementary Material 2. Mean effect sizes were considered significantly different from each other if their 95% CI did not overlap; they were considered significantly different from the default IPCC Tier I value (1%) if the 95% CIs did not overlap with 1%. To test the possibility of publication bias (studies showing no significant effects might not be published), the Rosenthal's fail-safe N test was used (Rosenthal, 1979).

2.5. Case study: effect of EF choice on Spanish N_2O emissions estimation

We chose Spain to examine the effect of applying the EFs found in this study because Spain includes both rain-fed and irrigated crops, and has one of the largest agricultural land uses within Europe. In addition, nutrient budgets at the regional scale have been well developed for Spain (Lassaletta et al., 2014; Sanz-Cobena et al., 2014b). We processed the information provided by MMARM (2010) on N fertilizer use (organic and synthetic) for rain-fed and irrigated crops (by surface) in Spanish NUTS3 regions to estimate the total input of fertilizer per climatic region (temperate and Mediterranean) and water management type. We then compared two methods to calculate the Spanish national N_2O emissions: 1) 'Current EF', we applied an EF=1.0% (IPCC, 2006) on the N inputs; 2) 'New EFs', the EFs obtained in this study for rain-fed, furrow, sprinkler and drip-irrigated systems in Mediterranean areas, and the IPCC 2006 EF for temperate areas in the cropping systems of northern Spain.

3. Results

3.1. Cumulative N_2O emissions and EF for Mediterranean regions

A considerable number of field studies analyzing N_2O emissions in Mediterranean areas has been published in the last 10 years from four of the five Mediterranean regions worldwide (see Supplementary Material 2 for regional description). The cumulative emissions during the experiment in fertilized plots ranged from –0.15 kg N_2O-N ha^{-1} in a rice crop in California (Simmonds et al., 2015) to 43.3 kg N_2O-N ha^{-1} in a maize field in Israel (Heller et al., 2010), with a mean value of 2.8 kg N_2O-N ha^{-1}. Regarding irrigation, N_2O emissions were on average largest for drip irrigation (4.6 kg N_2O-N ha^{-1}) and smallest for flooded irrigation (0.5 kg N_2O-N ha^{-1}) systems (Table 2). Synthetic fertilizers were the dominant type of fertilizer in all irrigation systems (Fig. S2) with drip irrigation systems receiving the most N fertilizer (295 kg N ha^{-1}), with some cases of extremely high (1500 kg N ha^{-1}) application rates (Heller et al., 2010). When considering the different fertilizers, treatments with a mixture of organic-synthetic fertilizers emitted the most cumulative N_2O (9.8 kg N_2O-N ha^{-1}), which is related to the high average N application rate in this group (535 kg N ha^{-1}). Organic-liquid fertilizers were applied at similar rates as synthetic fertilizers, but their emissions were on average higher (4.8 vs. 1.7 kg N_2O-N ha^{-1}). The use of organic-solid fertilizers or the addition of inhibitors led to the lowest average cumulative emissions (1.8 and 1.2 kg N_2O-N ha^{-1}, respectively) (Table 2). Maize and horticulture crops had the highest N_2O emissions (4.7 and 3.4 kg N_2O-N ha^{-1}), while rice and cereal crops had the lowest (0.5 and 0.7 kg N_2O-N ha^{-1}) (Table 2).

The mean EF for Mediterranean crops (EF_{Med})—covering rain-fed and irrigated systems, arable and permanent crops, organically and synthetically fertilized systems (treatments with inhibitors excluded) for all Mediterranean-type climate areas—was 0.50%±0.12 (EF_{Med}±95%CI, N=200; Rosenthal's fail-safe test: 4830). Grouping into different categories allowed us to identify which factors (soil, crop, irrigation system, type of fertilizer and application rate) had a significant impact on averaged EFs, providing key information when proposing N_2O mitigation strategies.

3.2. Influence of soil characteristics on EF

Soil pH, soil organic C or soil texture did not significantly affect EFs. Soil pHs ranged from 4.8 in a rice experimental station field site in California (Simmonds et al., 2015) to 8.5 in a cereal crop in north-eastern Spain (Plaza-Bonilla et al., 2014), with most soils having a neutral to alkaline pH (in 83% of the cases, pH>7). The concentration of organic C in soils ranged from 4 g C kg^{-1} soil in a *Typic Haplargids* in California (Schellenberg et al., 2012) to 133 g C kg^{-1} soil in an

Andisol in Chile (Vistoso et al., 2012), and the average soil organic C concentration was 15.9 g C kg^{-1} soil. EFs did not significantly differ among soils with low (EF: 0.56, N=59), medium (EF: 0.51, N=94) or high (EF: 0.37, N=5) organic C concentrations. Finally, soil texture had no significant effect on average EFs, although trends suggested that larger EFs could be expected from coarse (EF: 0.58%, N=77) and medium-textured soils (EF: 0.48%, N=100), than from fine-textured soils (EF: 0.27%, N=22).

3.3. Influence of water management on EF

Rain-fed systems had an average EF of 0.27%±0.21 (N=62) which was significantly lower than 1% (Fig. 2). Studies under dry Mediterranean conditions (average annual precipitation <450 mm) had lower EFs (EF: 0.21%±0.26, N=38) than studies in areas with an average annual precipitation >450 mm (EF: 0.32%±0.33, N=24).

There was high variability in EFs between types of irrigation management (Fig. 2). Drip-irrigated (including both surface and subsurface) and furrow systems had lower EFs (EF: 0.51%±0.26, N=52 and EF: 0.47%±0.36, N=27, respectively) than sprinklers (EF: 0.91%±0.24, N=45), which was close and not significantly differ from the IPCC default EF.

It is important to note that drip-irrigated systems had the highest level of N fertilization (Table 2), which could have biased the results of the meta-analysis, increasing the EF for this group. Flooded systems (rice fields) had the lowest EF (0.19%±0.50, N=14), in line with IPCC (2006) guidelines.

3.4. Influence of fertilizer type and application rate on EF

The effect of nitrogen fertilizer type and application rate is shown in Figure 3. The highest EFs corresponded with organic-liquid fertilizers (EF: 0.85%±0.30, N=30), which were mostly pig or cattle slurries, or the liquid fraction of their digestates; this EF did not significantly differ from 1%. The rest of the fertilizer types had an EF significantly lower than 1% but were statistically similar to each other. The use of nitrification/urease inhibitors decreased the average EFs (EF: 0.14% ±0.32, N=23) when compared with synthetic, organic-liquid, and mixtures of organic and synthetic fertilizers, but was similar to EFs from organic-solid fertilizers (EF: 0.19% ±0.33, N=24). Crops fertilized with organic-solid fertilizers received, on average, almost double the amount of N than those with synthetic or liquid fertilizers (Table 2), which reinforces organic-solid fertilization as a strategy to decrease EFs. Although not statistically significant, higher N application rates increased EFs. Low N application rates (<100 kg N ha^{-1}) had the lowest EFs (EF: 0.27%, N=40), whereas high N application rates (>400 kg N ha^{-1}) resulted in EFs that did not significantly differ from the 1% IPCC value (EF: 0.82%, N=15).

3.5. Influence of crop types on EF

Crops could be categorized into six groups, five of which presented EFs significantly lower than 1% (Fig. 4). Rice and cereals (wheat, barley, and oat) had the smallest EFs (EF: 0.19%± 0.51, N=14 for rice and 0.26%±0.22, N=53 for cereals). Perennials (including vineyards, almonds, and olive orchards) and others (including pasture, legumes, rapeseed, crop rotations and bare soil) had intermediate EFs (EF: 0.54%, N=19 for perennials and EF: 0.47%, N=33 for others). Horticultural crops (melons, onions, tomatoes, and potatoes) showed a slightly higher than average EF (EF: 0.63%±0.31, N=34). Finally, maize had a relatively high average EF (EF: 0.83%±0.26, N=47) which did not significantly differ from the 1% default.

3.6. Case study: effect of EF choice on Spanish N_2O emissions estimation

Table 3 shows ‘current EF’ used by national inventories (IPCC, 2006) and the ‘New EFs’ determined from this study for rain-fed, furrow, sprinkler and drip-irrigated systems in Mediterranean crops. Nitrous oxide emissions from Spanish agriculture vary considerably depending on the calculation method. The emissions from Mediterranean Spanish agriculture calculated with the current EF (12.5 Gg N_2O-N yr^{-1}) exceeded the value using the new EFs (5.5 Gg N_2O-N yr^{-1}) by a factor of two and this had a substantial impact on total national emissions (Table 4).

4. Discussion

In this paper, we derived an EF for N_2O emissions from Mediterranean regions (EF_{Med}: 0.5%) and demonstrated that EFs in Mediterranean-cultivated lands are significantly lower than the 1% IPCC Tier I default value (IPCC, 2006) or the 1.25% (IPCC, 1996) used to calculate N_2O emissions in response to applying N fertilizer to land. We, therefore, recommend that Mediterranean countries, or regions, consider refining their national inventories to reflect the relatively small EF. Here, we show the implications of such a change by using the EFs obtained in this study to estimate total N_2O emissions from cropping systems in Spain and compare them to estimates using the IPCC default value.

To derive statistically robust estimates of EFs, we opted to retain studies without control measurements. We performed a sensitivity test (see Supplementary Material 2) which demonstrated that including these studies had no impact on the mean EF_{Med} (EF: 0.496% including all studies and EF: 0.463% excluding cases without control, see Supplementary Material 2). We, therefore, conclude that the EF_{Med} is robust, but due to the high heterogeneity of the studies included in the dataset, it was often difficult to find significant differences between different management strategies. Further field research, measuring emissions over the whole year and including control treatments, is merited to better quantify EFs for the various management options in Mediterranean systems.

4.1. Influence of soil characteristics.

We did not find significant differences in EFs based on soil characteristics. This finding seems to contradict previous studies where soil organic C concentration and pH had a clear impact on denitrification and therefore N_2O emissions (Li et al., 2005; Šimeck and Cooper, 2002). However, these relationships might be difficult to find in our dataset, where most soils had a neutral or slightly alkaline pH and similar (in general low) concentrations of organic C, with other variables having a stronger effect on N_2O emissions (N application rate, soil water content, type of fertilizer applied, etc.). In addition, although denitrification is generally identified as the major process generating N_2O in most cropping systems, this does not necessarily stand for studies under Mediterranean conditions, where the importance of nitrifier-nitrification and nitrifier-denitrification have been documented (Sánchez-García et al., 2014; Sánchez-Martín et al., 2008).

Although not significant, we found higher EFs in coarse/medium-textured soils (EF: 0.58 and 0.48%) than in fine-textured soils (EF: 0.27%). Since denitrification needs anaerobic conditions, which are more likely to occur in fine-textured soils, this result seems contradictory. Our finding might be related to (i) complete denitrification (transformation to N_2) in less-aerated fine-textured soils (Šimeck and Cooper, 2002) or (ii) nitrification processes having an important role in N_2O emissions, with higher nitrification rates in low water content, well-aerated soils (Thomsen et al., 2003). Also, previous studies found higher annual denitrification losses in loamy soils than sandy or clay-textured soils, which was interpreted as a limitation of C diffusion by adsorption to clays in fine-textured soils (Barton et al., 1999).

4.2. Consequences for N_2O mitigation strategies

Applying the new EFs has consequences for determining the effectiveness of N_2O mitigation strategies in Mediterranean regions, as baseline emissions will be smaller than those suggested by Tier I emission estimates. Mitigation options should, therefore, be assessed in light of these lower baseline emissions. We analyze this below for water and fertilizer management, and different cropping systems.

4.2.1. Water management

Among the irrigation technologies used in Mediterranean cropping systems, furrows are still widespread in summer-irrigated crops and sprinkler irrigation systems are on the increase in Spain (MAGRAMA, 2014). However, since many Mediterranean regions suffer from water scarcity, water-saving irrigation systems such as drip irrigation (both surface and subsurface) are being developed. The area sown to maize under drip irrigation is expected to increase due to higher water use efficiency, maintained crop yields and technical viability (Couto et al., 2013). Despite these advantages, the impact of drip irrigation systems on N_2O emissions is poorly documented.

Our analyses revealed that EFs for N_2O from drip-irrigated systems are much lower than those in which water is applied through sprinklers, even when the average N application rate was higher with drip irrigation. This is consistent with other field-based research (Kallenbach et al., 2010; Sánchez-Martín et al., 2008) and a previous review under Mediterranean conditions (Aguilera et al., 2013a). The reduction in N_2O emissions with drip irrigation is probably caused by a reduction in the rate of water application compared with other conventional systems (Sharmasarkar et al., 2001). This may decrease the soil-water-filled pore space (WFPS) below the optimum range for N_2O production through denitrification, which is 60–90% depending on soil type (Barton et al., 1999, Sanz-Cobena et al., 2014a). WFPS levels below this threshold have been observed in many of the drip irrigation studies included in this review. For instance, in Abalos et al. (2014), the WFPS was below 65% for 84% of the experimental period; it never exceeded 50% in the study of Schellenberg et al. (2012), and it ranged from 20–30% and 40–60% in Kallenbach et al. (2010) and Kennedy et al. (2013), respectively. Therefore, our results suggest that drip irrigation represents an effective N_2O mitigation practice in Mediterranean irrigated systems. These benefits, however, should be evaluated together with other effects on the greenhouse gas balance and further socioenvironmental consequences. For example, increased infrastructure material requirements and energy needs for pressurizing the irrigation water might offset drip irrigation N_2O-related emission savings in certain situations, while reduced water use (and related energy consumption) might be the main component responsible for emission reduction in other situations (Sanz-Cobena et al., this issue).

The lower EFs found under furrow irrigation compared to sprinkler irrigation might be related to a slightly lower average N application in the furrow systems included in our dataset and to a different soil wetting pattern, favoring total denitrification to N_2 after irrigation events in furrows (Sánchez-Martín et al., 2008).

Our results show that rain-fed crops with less than 450 mm rainfall and flooded systems have the lowest EFs of all systems (Fig. 2). In contrast, rain-fed crops in areas with annual precipitation greater than 450 mm have larger emissions. These findings show the strong effect of specific climatic conditions and soil moisture on the performance of Mediterranean cropping systems in terms of N_2O emissions. The distribution of rain inputs also plays a relevant role. The first rainfall after long periods of drought (common in summers of Mediterranean areas) usually triggers N_2O emissions. This pulsing effect, also observed in the dry areas of drip-irrigated crops, is due to the accumulation of mineral N in dry soils and the reactivation of water-stressed bacteria after rainfall events (Sánchez-Martín et al., 2010a; Skiba et al., 1997).

Drip irrigation may have an adverse side-effect as its use has been associated with enhanced emissions of nitric oxide (NO) (Abalos et al., 2014). This is because the lower WFPS may favor NO production from nitrification. Pilegaard (2013) reported maximum NO emissions at intermediate soil moisture (40–60% WFPS) since NO is highly reactive and will be consumed at higher soil moisture.

4.2.2. Fertilizer management

Our results suggest that the use of liquid manures and inorganic N fertilizers results in greater N_2O emissions than organic-solid fertilizers such as composted manures and green wastes. Liquid and inorganic N fertilizers are likely to be more readily available to plants and microorganisms, whereas solid organically-bound N requires decomposition and microbial mineralization to be used in N_2O-producing processes (Poodle et al., 2002). Composted organic fertilizer N is thus released more slowly, ultimately increasing N uptake by crops (Ryals et al., 2015) and decreasing the potential for N_2O emissions. It is notable that not all organic fertilizers are equivalent with regard to their potential effects on N_2O emissions. For example, fresh manures and manure slurries can result in relatively large N_2O emissions. A recent meta-analysis found the IPCC Tier II model underestimated N_2O emissions from cattle manure in the United States by an order of magnitude (Owen and Silver, 2015). Davidson (2009) also suggested that manure management was a dominant source of atmospheric N_2O concentrations, accounting for more than 40% of anthropogenic N_2O emissions. Liquid manures are rich in both N and C, potentially facilitating N_2O production in low C environments, mostly through denitrification. As already observed in Aguilera et al. (2013a), solid manure would result in lower N_2O emissions, unlike in more humid areas with relatively high decomposition rates and N_2O EFs (Owen et al., 2015).

As expected, nitrification/urease inhibitors effectively reduced EFs from Mediterranean systems (Mosier et al., 1996). In a recent review, Gilsanz et al. (2016) developed EFs of 0.42%±2.2 and 0.70%±3.3 for DCD and DMPP, respectively, two commonly used nitrification inhibitors. The lower EF found in this study (0.14%±0.32) agrees with the low baseline EFs found in the studies included in our dataset. Thus, inhibitors seem like a good strategy to mitigate direct N_2O emissions under Mediterranean conditions, although the potential is lowered by the relatively small baseline emissions in Mediterranean systems.

In agreement with previous studies (Kim et al., 2013; Shcherbak et al., 2014), increasing fertilizer application rates led to increased EFs. We found that applying N fertilizers over 400 kg N ha^{-1} resulted in EFs that did not significantly differ from the 1% IPCC Tier I default value. The lack of statistical significance between N doses is probably related to the fact that in our dataset most studies only considered one N application rate, with a limited number of cases with very low or high N fertilization rates.

4.2.3. Crop types

In a previous quantitative review of Mediterranean cropping systems, Aguilera et al. (2013a) observed that the differences in cumulative N_2O emissions among crop types clearly respond to the management characteristics of each crop type; our results confirm these conclusions. Generally, the crop types in which water and fertilizer applications are low (see Figs. S3 and S4 and Table 2), such as rain-fed crops (winter cereals), have the lowest N_2O response to N applications. A low EF for rice is associated with flooding which generates anaerobic conditions favoring complete denitrification to N_2, thereby reducing N_2O release from the soil (Conrad, 1996). Maize has a high EF, possibly because it is not irrigated with water-saving techniques and has on average higher N application rates. The wide confidence intervals observed for the EFs in perennials and rice are due to the lower number of observations within these crop categories.

4.3. Case study: effect of EF choice on Spanish N_2O emissions estimation

In this work we have seen how the application of EFs adapted to Mediterranean conditions can significantly reduce the national estimates of total N_2O emissions from cropping systems. The level of indirect emissions is, however, highly uncertain, and published information is scarce, and has thus not been assessed in this study. IPCC Tier I proposes an EF for indirect emissions of 0.75% while Garnier et al. (2009, 2013) estimated that, for the Seine temperate basin, indirect emissions represented 13–17% of total direct emissions. Due to the regulation of water in Mediterranean agricultural areas in Spain through a dense drainage network and reservoirs (Aguilera et al., 2015), the potential for denitrification could be high and could, therefore, generate high indirect emissions. The magnitude of indirect N_2O emissions in Mediterranean areas is an interesting area for future research.

5. Concluding remarks

The average EF for nitrous oxide emissions in Mediterranean cropping systems was 50% lower than the IPCC Tier I default value (1%), which is largely based on values observed in temperate regions. The most important factors controlling the magnitude of soil N_2O EFs from Mediterranean regions were water regime (irrigation technique or precipitation amount) and fertilizer type and application rate. In rain-fed systems with precipitation below 450 mm, the EF is much lower than the IPCC values. The EF for sprinkler-irrigated systems is similar to that for temperate cropping systems, whereas drip-irrigated systems have a high potential for mitigation (EF: 0.51%). The N fertilizer rate altered EFs, suggesting a non-linear relationship between N_2O emissions and N application rate. Intensive cropping systems, such as irrigated maize, tended to have higher EFs than less intensive systems such as cereals.

Applying specific EFs would lower estimates of total N_2O emissions in countries with large areas of agricultural soils in Mediterranean climates. For example, applying current Tier I EFs to Spanish cropping systems leads to a total N_2O emission estimate that is a factor of two higher than when applying the new EFs from our analysis (14 Gg N_2O-N yr^{-1} vs. 7 Gg N_2O-N yr^{-1}). Our results indicate that N_2O emissions from Mediterranean agriculture are much lower than expected and that with the new EFs, the effect of mitigation strategies such as drip irrigation or using nitrification inhibitors, even if highly significant, may be smaller in absolute terms (since baseline emissions will be lower).

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Figure captions

Fig. 1. Location of the study sites included in the dataset. The dark gray area delimits the Mediterranean biome from the collection of ecoregions mapped by the World Wildlife Fund (Olson et al., 2001).

Fig. 2. The influence of different irrigation options on changes in N_2O emission factors (EFs) in Mediterranean-type climate areas. Symbols represent mean effect sizes [EFs (%)] with 95% confidence intervals. The numbers shown in parentheses correspond to observations in each class upon which the statistical analysis was based. For this analysis, treatments with nitrification inhibitors were excluded (see Methods).

Fig. 3. The impact of the type of N fertilizer and application rate on changes in N_2O emission factors (EFs) in Mediterranean-type climate areas. Symbols represent mean effect sizes [EFs (%)] with 95% confidence intervals. The numbers shown in parentheses correspond to observations in each class upon which the statistical analysis was based.

Fig. 4. Average N_2O emission factors (EFs) in Mediterranean-type climate areas depending on the type of crop. Symbols represent mean effect sizes [EFs (%)] with 95% confidence intervals. The numbers shown in parentheses correspond to observations in each class upon which the statistical analysis was based. For this analysis, treatments with nitrification inhibitors were excluded (see Methods).

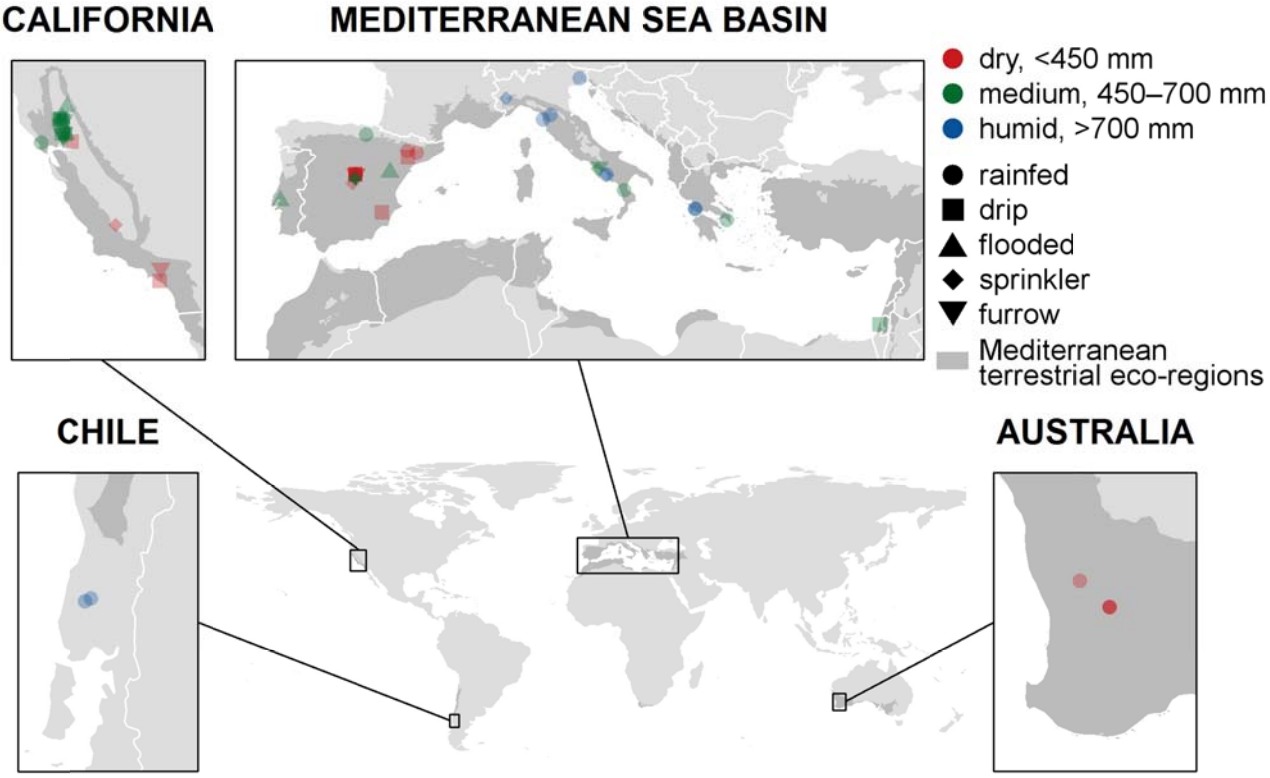

CALIFORNIA
MEDITERRANEAN SEA BASIN
CHILE
AUSTRALIA
● dry, <450 mm
● medium, 450–700 mm
● humid, >700 mm
● rainfed
■ drip
▲ flooded
◆ sprinkler
▼ furrow
▬ Mediterranean terrestrial eco-regions

Figure 1

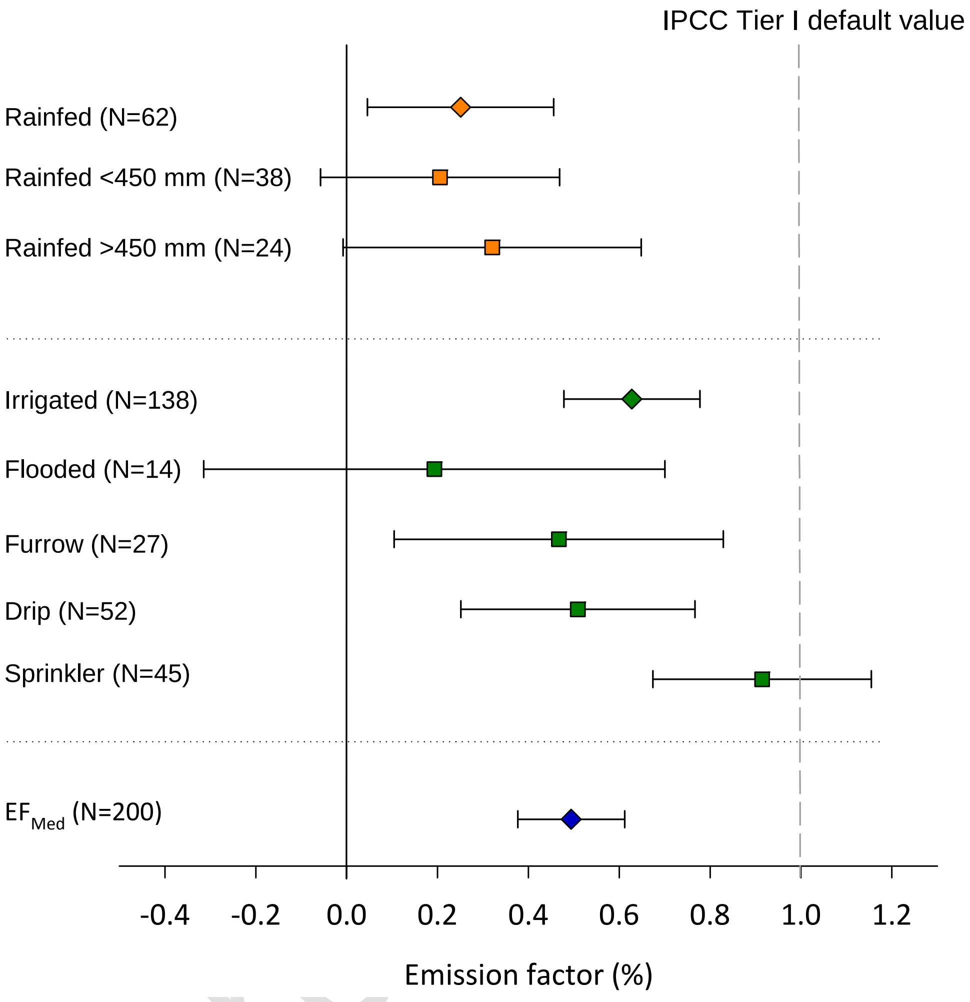

IPCC Tier I default value
Rainfed (N=62)
Rainfed <450 mm (N=38)
Rainfed >450 mm (N=24)
Irrigated (N=138)
Flooded (N=14)
Furrow (N=27)
Drip (N=52)
Sprinkler (N=45)
EF_{Med} (N=200)
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Emission factor (%)

Figure 2

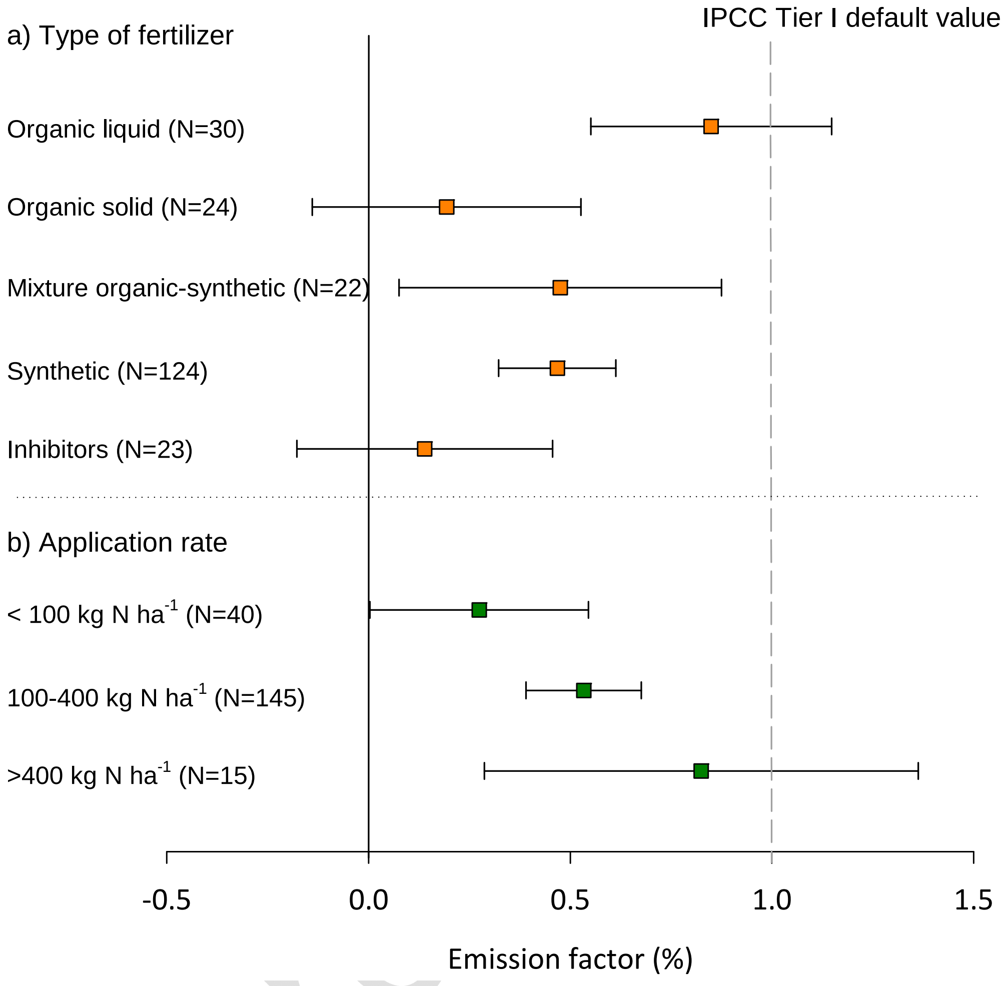

a) Type of fertilizer
IPCC Tier I default value
Organic liquid (N=30)
Organic solid (N=24)
Mixture organic-synthetic (N=22)
Synthetic (N=124)
Inhibitors (N=23)
b) Application rate
< 100 kg N ha^{-1} (N=40)
100-400 kg N ha^{-1} (N=145)
>400 kg N ha^{-1} (N=15)
-0.5
0.0
0.5
1.0
1.5
Emission factor (%)

Figure 3

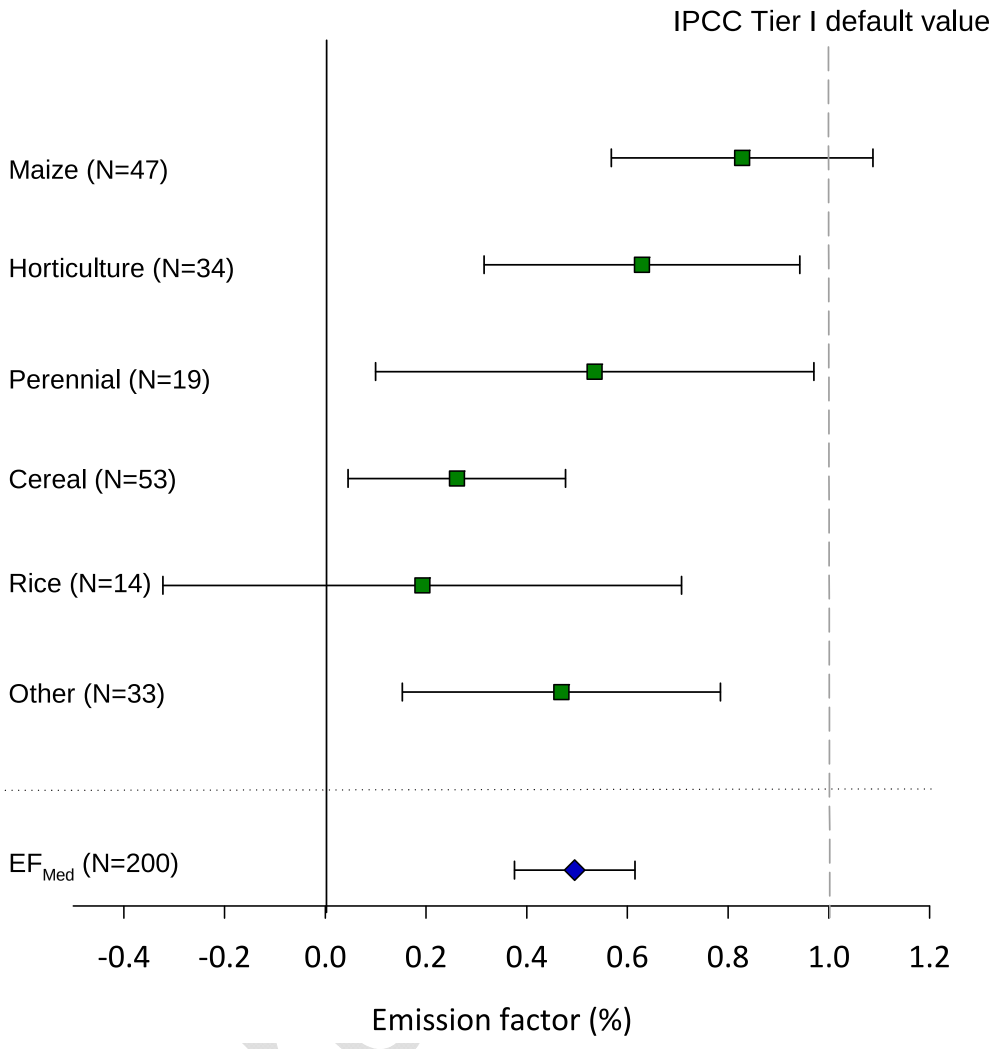

IPCC Tier I default value
Maize (N=47)
Horticulture (N=34)
Perennial (N=19)
Cereal (N=53)
Rice (N=14)
Other (N=33)
EF$_{Med}$ (N=200)
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Emission factor (%)

Figure 4

Table 1. Studies included in the meta-analyses

Mediterranean-type climate area	Country	Studies
Mediterranean Basin	Spain	(Abalos et al., 2012, 2013, 2014; Huérfano et al., 2015; López-Fernández et al., 2007; Maris et al., 2015a, 2015b; Meijide et al., 2007, 2009; Plaza-Bonilla et al., 2014; Sánchez-García et al., 2016; Sánchez-Martín et al., 2008, 2010a, 2010b; Sanz-Cobena et al., 2012, 2014a; Tellez-Rio et al., 2015; Vallejo et al., 2005, 2006, 2014)
	Italy	(Alluvione et al., 2010; Bosco et al., 2015; Castaldi et al., 2011; Pappa et al., unpublished data; Ranucci et al., 2011; Rees et al., 2013; Vitale et al., 2013)
	Israel/Portugal/ Greece	(Heller et al., 2010; Kontopoulou et al., 2015, unpublished data; Pappa et al., 2016; Pereira et al., 2013)
Australia	Australia	(Barton et al., 2008, 2010, 2013; Li et al., 2011)
California	USA	(Alsina et al., 2013; Angst et al., 2014; Garland et al., 2011, 2014; Kallenbach et al., 2010; Kennedy et al., 2013; Kong et al., 2009; Lee et al., 2009; Pittelkow et al., 2013; Schellenberg et al., 2012; Simmonds et al., 2015; Suddick and Six, 2013; Townsend-Small et al., 2011; Verhoeven and Six, 2014; Zhu-Barker et al., 2015)
Chile	Chile	(Hube et al., 2016; Vistoso et al., 2012)

Table 2. The number of observations (N), mean and standard deviation (SD) of cumulative N_2O emissions, N application rate and experiment duration for some of the factors with a significant influence on N_2O emissions from agricultural fields.

	Cumulative N_2O emissions (kg N_2O-N ha^{-1})			**N application rate (kg N ha^{-1})**		**Experiment duration (days)**	
	N	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Water							
Drip	55	4.6	9.5	295	387	299	110
Flooded	14	0.5	0.8	161	59	277	106
Furrow	29	2.9	4.7	205	94	254	92
Sprinkler	55	3.7	3.3	226	75	186	99
Rain-fed <450 mm	39	0.4	0.3	117	58	269	66
Rain-fed >450 mm	40	2.3	4.8	153	125	253	131
Fertilizer type							
Organic-liquid	30	4.8	5.4	172	95	251	71
Organic-solid	26	1.8	2.3	238	155	227	114
Mixture	22	9.8	13.5	535	523	327	73
Synthetic	131	1.7	3.1	157	77	260	108
Inhibitor*	23	1.2	1.7	167	78	167	129
Crop type							
Maize	56	4.7	7.0	323	298	223	129
Horticulture	36	3.4	4.6	182	67	231	125
Perennial	22	1.2	1.5	104	73	297	100
Cereal	61	0.7	0.6	138	62	277	68
Rice	14	0.5	0.8	161	59	277	106
Others	43	4.5	8.8	230	290	243	112

*inhibitor refers to treatments with synthetic and/or organic fertilizers where nitrification or urease inhibitors were applied.

Table 3. Emission factors (EFs) used to estimate total N_2O emissions in the Spanish cropping systems: current EFs according to IPCC (2006) and the new values for Mediterranean areas developed in this work for different irrigation systems. The percentages in brackets show the proportion of the area under each irrigation system in Spain.

	EFs	Temperate climate	Mediterranean climate
Current	Rain-fed crops	1.0%	1.0%
	Irrigated crops	1.0%	1.0%
New EFs	Rain-fed crops	1.0%	0.27%
	Irrigated furrow (27% surface)	1.0%	0.47%
	Sprinkler (24% surface)	1.0%	0.91%
	Drip (49% surface)	1.0%	0.51%

Table 4. Comparison of total N_2O emissions in Spanish cropping systems (MMARM, 2010) after the application of the current EFs and the new EFs obtained in this study, considering that all the irrigated crops are furrow, sprinkler or drip irrigated. The percentages in brackets show the proportion of the area under each irrigation system in Spain.

		Temperate climate	Mediterranean climate	Total
Fertilizer N input (synth + org) (Gg N yr^{-1})	Rain-fed crops	137	585	722
	Irrigated crops	13	664	678
	Total	**151**	**1249**	**1400**
Current EFs	Rain-fed crops	1.4	5.8	7.2
Total N_2O emissions	Irrigated crops	0.1	6.6	6.8
(Gg N yr^{-1})	**Total**	**1.5**	**12.5**	**14.0**
	Rain-fed crops	1.4	1.6	3.0
New EFs	Furrow (27%)	0.0	0.8	0.9
Total N_2O emissions	Sprinkler (24%)	0.0	1.5	1.5
(Gg N yr^{-1})	Drip (49%)	0.1	1.7	1.7
	Total	**1.5**	**5.5**	**7.0**

Supplementary Material 2

Supplementary methods

Missing data. Many studies in our dataset (approx. 40%) did not include a control without N fertilizer. In those cases, it is not possible to calculate the 'true EF' according to the equation:

$$EF\ (\%) = \frac{N_2O_{treatment}\ - N_2O_{control}}{applied\ N} * 100$$

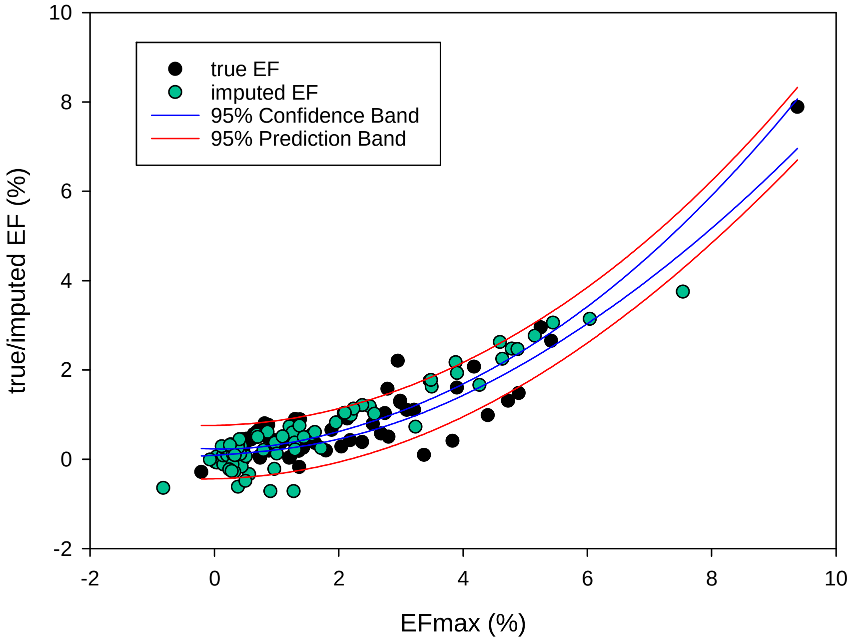
where $N_2O_{treatment}$ and $N_2O_{control}$ represent the cumulative N_2O emissions from the fertilized treatment and the control without fertilizer (kg N_2O-N ha^{-1}). The difference is divided by the amount of N applied in the fertilized treatment (kg N ha^{-1})

We used the full set of studies for the prediction of missing data through multiple imputation by chained equations (regression method) with IBM SPSS Statistics 24 (Schafer, 1999). We included soil characteristics, crop type, water management, fertilizer type, fertilizer rate, $N_2O_{treatment}$ and $N_2O_{control}$ as predictor variables and $N_2O_{control}$ as the target (predicted) variable. We selected the Mersenne Twister random number generator with the default fixed starting point given by SPSS (2000000). We performed 10 imputations, from which we calculated the average imputed value for each $N_2O_{control}$ that was lacking.

In addition, for all cases, we calculated the maximum EF (EF_{max}), assuming that all N-N_2O derived from the applied fertilizer and the baseline emission were zero, that is:

$$EFmax\ (\%) = \frac{N_2O_{treatment}}{applied\ N} * 100$$

For the cases where we could calculate both 'true EF' and 'EFmax' (140 cases, black circles in Fig. S1), we found a highly significant correlation between these two values (P<0.001). We plotted the imputed values (green circles) to discard any possible outliers from the imputed dataset. We discarded cases 120, 167, 183, 185 and 202–206 because the imputed data for these cases were too far from the general observed data trend and they could bias subgroup means.



Meta-analysis

We used the emission factor (EF) as the effect size in our meta-analysis. We did so because the outcomes in our dataset ($N_2O_{treatment}$ and $N_2O_{control}$) were reported on the same scale (kg N_2O-N ha^{-1}) in all studies, so the raw mean difference is intuitively meaningful.

$$Effect\ size\ =\ EF\ (\%) = \frac{N_2O_{treatment}\ - N_2O_{control}}{applied\ N} * 100$$

Weighting functions. We used a non-parametric function, based on sample size, for weighting (Adams et al., 1997). We chose this function instead of the variance because the variance correlated with the EF (P<0.0001) which could bias the results giving more weight to studies with small N_2O emissions. The sample size weight function used here is:

$$w\ = \frac{N_{treatment} * N_{control}}{(N_{treatment} + N_{control})}$$

where w is the weight given to each particular case, $N_{treatment}$ and $N_{control}$ are the number of replicates for the treatment and control, respectively. In the cases where controls were imputed, we chose $N_{control} = 1$ to give less weight to cases without a control. We rescaled the weights by 1.2 to apply a random effects model. We performed a sensitivity test and checked that this did not have an impact on EFs.

Sensitivity tests

To test the validity of our assumptions, we performed sensitivity tests. We compared the results of the meta-analysis performed using the entire dataset (including imputed data for controls) with the 'complete case' meta-analysis, i.e. leaving out all studies that originally did not report the control measurement. We found that both meta-analyses lead to similar cumulative effect sizes (EF_{Med} = 0.496%±0.12 with the entire dataset and EF_{Med} = 0.462±0.14 excluding cases without a control).

Results for the different groups were similar (except for drip irrigation and perennials). When excluding cases without a control, higher CIs were obtained (see Table S1).

Table S1. Number of observations (N), emission factors (EF) and 95% confidence intervals (95% CI) obtained by using the entire dataset (with imputed values for missing controls) and by taking a “complete case” analysis (excluding cases without control).

	Entire dataset (with imputed controls)			**Excluding cases without control**		
	N	**EF**	**95% CI**	**N**	**EF**	**95% CI**
Water						
Drip	52	0.5090	0.2512 – 0.7668	14	0.1469	–0.3022 – 0.5959
Flooded	14	0.1930	–0.3148 –0.7008	8	0.1946	–0.4881 – 0.8772
Furrow	27	0.4669	0.1046 – 0.8291	11	0.3541	–0.1944 – 0.9026
Sprinkler	45	0.9147	0.6743 – 1.1552	41	0.9567	0.6990 – 1.2144
Rain-fed <450 mm	39	0.2054	–0.0577 – 0.4684	35	0.2144	–0.0661 – 0.4949
Rain-fed >450 mm	24	0.3203	–0.0079 – 0.6486	12	0.2646	–0.1713 – 0.7005
Fertilizer type						
Organic-liquid	30	0.8495	0.5506 – 1.1485	24	0.6715	0.3247 – 1.0183
Organic-solid	24	0.1934	–0.1398 – 0.5266	15	0.3165	–0.1117 – 0.7447
Mixture	22	0.4742	0.0720 – 0.8764	7	0.4089	–0.3507 – 1.1685
Synthetic	124	0.4680	0.3225 – 0.6135	75	0.4355	0.2518 – 0.6192
Inhibitor	23	0.1391	–0.1779 – 0.4561	18	0.1604	–0.2518 – 0.6192
Crop type						
Maize	47	0.8282	0.5684 – 10.880	26	0.9981	0.6609 – 1.3352
Horticulture	34	0.6290	0.3156 – 0.9425	18	0.5636	0.1486 – 0.9787
Perennial	19	0.5353	0.1004 – 0.9702	6	0.0609	–0.7317 – 0.8535
Cereal	53	0.2614	0.0452 – 0.4775	50	0.2662	0.0357 – 0.4966
Rice	14	0.1929	–0.3228 – 0.7087	8	0.1946	–0.5032 – 0.8924
Others	33	0.4691	0.1528 – 0.7854	13	0.4497	–0.0252 – 0.9246

Correlation between the different key variables

Fig. S2. Water management vs. fertilizer type

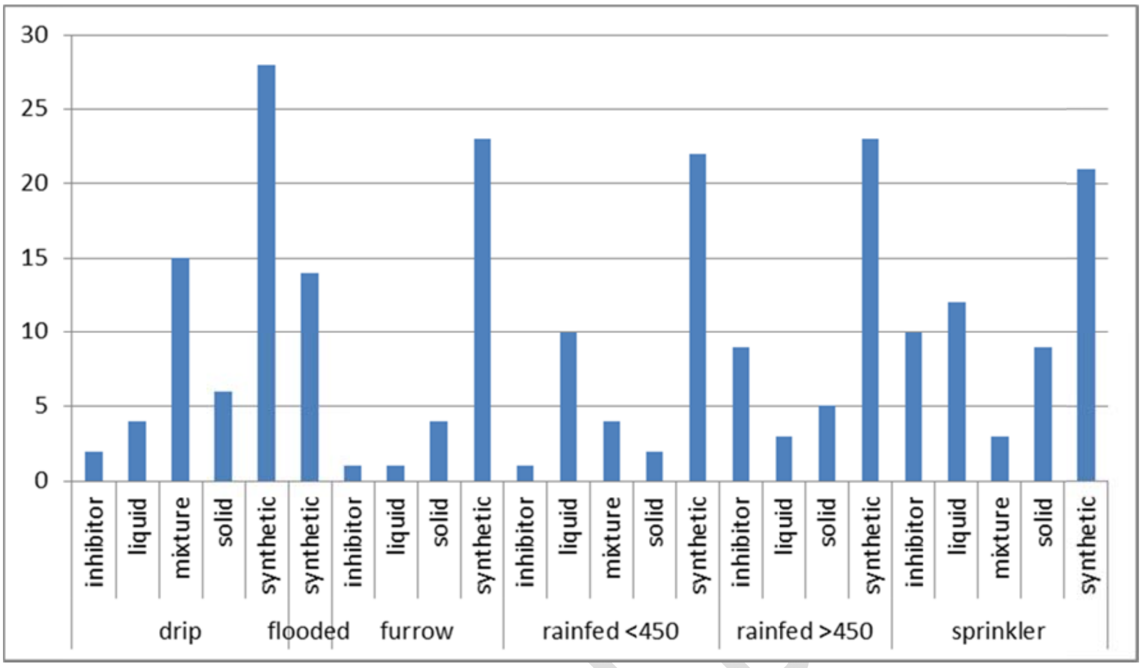
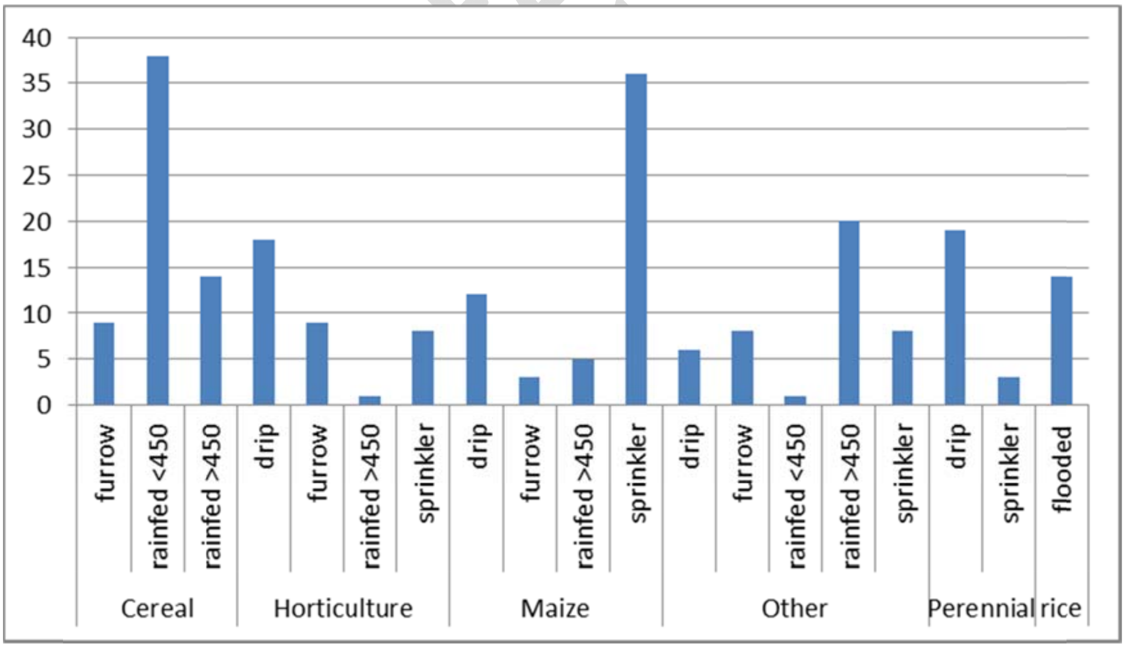
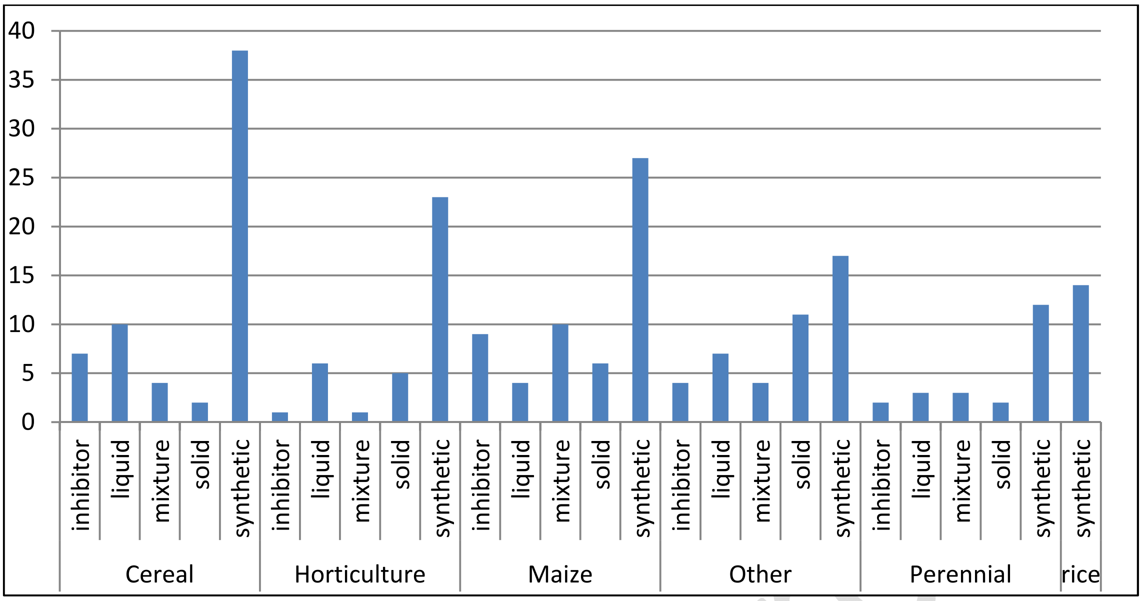


Fig. S3. Crop type vs. water management



993 **Fig. S4. Crop type vs. fertilizer type**



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Main characteristics of the studies found in each region

Mediterranean Sea Basin

The Mediterranean Basin represents 60% of the studies included in the dataset. While N_2O emissions were determined for a variety of crops in this region (perennial crops, horticulture, cereals, rice, legumes), these studies do not represent the broad range of crops and management conditions in the area. Cereals (maize, barley, and wheat) represented 60% of the cases, perennial crops were underrepresented with only two recent studies in olive orchards (Maris et al., 2015; Sánchez-García et al., 2016) and important crops such as vineyards and citrus were absent. Also, studies in Mediterranean France and Maghreb countries were lacking.

The average duration of the studies was 225 days, with 35% showing annual emissions. The methodology used for N_2O sampling was the closed chamber technique, with an average measurement frequency of once every nine days (although most studies concentrated measurements after fertilization and irrigation events).

Australia

In Australia, a Mediterranean climate occurs in south-western Australia, in the states of South and Western Australia. A variety of crops is grown, including cereals, oilseeds, and grain legumes. Crops are predominately rain-fed and consequently grown from early autumn through to late spring each year. Inorganic N fertilizer is applied to cereal and oilseed crops throughout the region with the reliance on inorganic N fertilizer increasing with the decline in legumes in the region's cropping rotations (Crews and Peoples, 2004). Minimum tillage practices dominate the region due to the fragile and highly weathered nature of Australia's ancient soils.

Nitrous oxide EFs have only been determined for study sites located in the grain-belt of Western Australia (Barton et al., 2008, 2010, 2013b; Li et al., 2011). This region includes approximately 18 million ha of arable land that produces up to 40% of Australia's annual grain production (Australian Bureau of Agricultural and Resource Economics and Sciences, www.agriculture.gov.au/abares).

Nitrous oxide emissions were determined by measuring N_2O fluxes on a sub-daily basis for approximately one year using soil chambers connected to a fully automated system. Nitrous oxide EFs ranged from 0.01 to 0.06% (median, 0.02%) for Mediterranean regions in south-western Australia and from five annual studies. In some instances, N_2O fluxes from N-fertilized treatments did not differ statistically from non-fertilized treatments (Barton et al., 2008). A large proportion of the N_2O fluxes from cropped soils in south-western Australia has been measured in response to summer rainfall events (Barton et al., 2008, 2010, 2013b) rather than following N fertilizer applications. Summer rainfall elevated soil water contents at times when surface soils were mild to warm (i.e. >15°C), resulting in rapid mineralization of soil organic matter and the production of mineral N. Furthermore, during these periods, there was no active plant growth to compete with soil microbial processes for available soil N.

Consequently, it has been hypothesized that the increased N_2O emissions following summer rainfall were probably coupled with an increase in ammonium availability and nitrification activity, although the contribution of denitrification in the region cannot be ruled out (Barton et al., 2013a). Nitrous oxide emissions following summer rainfall were often unpredictable and short-lived (<24 h) and would not have been characterized without using an automated measuring system (Barton et al., 2015).

California

California's agricultural ecosystems supply over one-third of the vegetables and two-thirds of the fruits and nuts grown in the U.S. and nearly 15% of the country's exports (CDFA, 2015). Twenty-seven percent of the studies included in this analysis were conducted in California, particularly from the agriculturally productive Central Valley. Field sites spanned six soil orders (Alfisols, Aridisols, Mollisols, Entisols, Inceptisols, and Vertisols) and a range of cropping systems including almonds, vineyards, tomatoes, maize, wheat, vegetable rotations, rice, and ryegrass. These crops represent only a small portion of the state's >400 agricultural commodities (CDFA, 2015). Most studies were designed to compare management practices including furrow and drip irrigation (Alsina et al., 2013; Kallenbach et al., 2010; Kennedy et al., 2013), standard and conservation tillage (Garland et al., 2011; Kong et al., 2009; Lee et al., 2009), and fertilizer application rates, type, or methods (Pittelkow et al., 2013; Schellenberg et al., 2012; Zhu-Barker et al., 2015). A few were observational across time (Garland et al., 2014), ecosystem (Townsend-Small et al., 2011), or cultivar types (Simmonds et al., 2015). Three studies tested the effects of biochar on N_2O emissions (Angst et al., 2014; Suddick and Six, 2013; Verhoevenand Six, 2014).

All studies in this region employed the vented static flux chamber method (Hutchinson and Mosier, 1981). Several experimental designs included daily sampling for several days after management events. Of the 15 studies, only two included an unfertilized control. Lowest fluxes were observed from flooded rice paddies, while highest fluxes were observed with furrow irrigation, standard tillage, and with the use of winter cover crops. Conservation tillage and drip irrigation tended to reduce N_2O emissions (e.g. Kallenbach et al., 2010; Kennedy et al., 2013), suggesting the importance of soil and water management in reducing total emissions.

Chile

Chile extends from the Atacama Desert in the north to Patagonian rangeland in the south (4,300 km). The central part of Chile is dominated by a Mediterranean climate with a mean rainfall of 300–1,000 mm. Further south, the country is dominated by a temperate climate with 1,300–2,500 mm yr^{-1}. Within this area, 60% of the land dedicated to agriculture is based on volcanic soils (Oenema et al., 2014).

Chile is highly vulnerable to the effects of climate change. Model predictions for the south of the country (35° to 45°S) indicate that a 0.5–1°C increase in temperature and a 5–15% reduction in rainfall can be expected from 2010–2040. These values would elevate to a 1.5–2.5°C temperature increase from 2040–2070, while the rainfall reduction would remain the same (MMAC, 2015). Additionally, the risk of droughts has increased significantly in the area since the second half of the 20th century; it is expected that towards the end of the 21st century this phenomenon will occur more than 10 times in 30 years (CEPAL, 2012). As an example, in the area of the study reported here, the 2014–2015 season was the driest agricultural season in the last 50 years, with a rainfall deficit of 50.4% for the spring–summer period (October to April). The 2015–2016 agricultural season presented a 29.1% rainfall deficit during the same period, compared with an average year (437.4 mm from October–April). This would result in areas traditionally defined as having a temperate climate to be reconsidered as transitional areas to Mediterranean-like conditions, with implications for traditional rainfed cropping systems.

Volcanic soils are characterized by low nutrient availability, high phosphorus (P) fixation capacity, high organic matter (OM) content and a pH-dependent cation exchange capacity (Escudey et al., 2001). High soil OM has been associated with specialized microbial and abiotic retention processes which immobilize N significantly reducing the potential for N losses to the wider environment, including gaseous losses (Cárdenas et al., 2013; Huygens et al., 2008).

Nitrous oxide emissions have been obtained mainly by using the static chambers technique (Muñoz et al., 2011; Vistoso et al., 2012) with its associated limitations. The relatively recent inclusion of semi-automated systems with sampling conducted on a sub-daily basis represents an opportunity to improve the resolution of the information generated (Hube et al., 2016). This could lead to the use of models adapted to local conditions as well as the integrated analysis of N_2O emissions and C capture in soils, with implications for the development of more integral mitigation practices that could favor farmer adoption.

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