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Mapping direct N_2O emissions from peri-urban agriculture: The case of the Metropolitan Area of Barcelona

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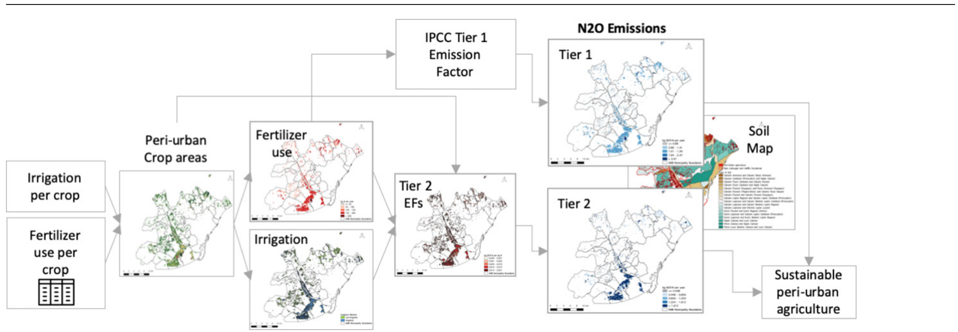
HIGHLIGHTS

- Spatially explicit direct N_2O emissions maps from peri-urban agriculture are rare
- There is lack of relevant datasets to estimate N_2O emissions at peri-urban scale
- We created maps of N_2O emissions, harnessing bottom-up data of relevant factors
- N_2O emissions maps tackles spatial variability but carry uncertainty of data used
- N_2O emissions maps highlight opportunities for sustainable peri-urban agriculture

GRAPHICAL ABSTRACT



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ABSTRACT

Geographically explicit datasets reflecting local management of crops are needed to help improve direct nitrous oxide (N_2O) emission inventories. Yet, the lack of geographically explicit datasets of relevant factors influencing the emissions make it difficult to estimate them in such way. Particularly, for local peri-urban agriculture, spatially explicit datasets of crop type, fertilizer use, irrigation, and emission factors (EFs) are hard to find, yet necessary for evaluating and promoting urban self-sufficiency, resilience, and circularity. We spatially distribute these factors for the peri-urban agriculture in the Metropolitan Area of Barcelona (AMB) and create N_2O emissions maps using crop-specific EFs as well as Tier 1 IPCC EFs for comparison. Further, the role of the soil types is qualitatively assessed. When compared to Tier 1 IPCC EFs, we find 15% more emissions (i.e. 7718 kg N_2O-N year^{-1}) than those estimated with the crop-specific EFs (i.e. 6533 kg N_2O-N year^{-1}) for the entire AMB. Emissions for most rainfed crop areas like cereals (e.g. oat and barley) and non-citric fruits (e.g. cherries and peaches), which cover 24% and 13% of AMB's peri-urban agricultural area respectively, are higher with Tier 1 EF. Conversely, crop-specific EFs estimate higher emissions for irrigated horticultural crops (e.g. tomato, artichoke) which cover 33% of AMB's peri-urban agricultural area and make up 70% of the total N_2O emissions (4588 kg N_2O-N year^{-1} using crop-specific EFs). Mapping the emissions helps evaluate spatial variability of key factors such as fertilizer use and irrigation of crops but carry uncertainties due to downscaling regional data to represent urban level data gaps. It also highlighted core emitting areas. Further the usefulness of the outputs on mitigation, sustainability and circularity studies are briefly discussed.

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1. Introduction

In the past century, agriculture has experienced an exponential growth to meet the food demand of an increasing global population (Albanito et al., 2017). This agricultural transformation has intensified agricultural systems and led towards the substantial use of nitrogen (N) fertilizer. As global food demand is expected to increase, further pressure will be added on agricultural soils by increasing N use (Muller et al., 2017). Yet, over half of the N fertilizer applied to agricultural soils globally is being lost, as only 47% of N applied is utilized to produce crops (Lassaletta et al., 2014).

Direct nitrous oxide (N_2O) is dissipated to the air when there are excessive N inputs to agricultural soils, which then influence microbial processes of nitrification and denitrification. Nitrification occurs in aerobic conditions and can be described as the oxidation of ammonium to nitrate. Denitrification occurs in anaerobic conditions and can be described as the reduction of nitrate to molecular N (Leip et al., 2011). N_2O is a greenhouse gas (GHG) that contributes to ozone depletion and climate change. At a global level, croplands are the main anthropogenic source of direct N_2O emissions (Wang et al., 2020). Global cropland N_2O emissions estimated by bottom-up approaches ranged between 1.5 and 5.0 Tg N year^{-1} (Wang et al., 2020).

There are several ways to estimate direct N_2O emissions. The use of emission factors (EFs) is among the most common ones. An N_2O EF can be defined as the mean emission rate per unit of N applied (kg N_2O-N/kg N applied) (De Klein et al., 2006; Yue et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) provides broadly used guidelines for estimating direct N_2O emissions from agricultural soils. The "Tier 1" methodology uses a default EF of 0.01 kg N_2O-N/kg N, assuming that 1% of N applied to agricultural soils, in the form of mineral and organic N applications, including crop residues and mineralization of soil organic carbon, will be released into the atmosphere as N_2O (De Klein et al., 2006). Nonetheless, this EF overlooks other key factors when determining N_2O direct emissions.

In fact, several studies (Bouwman et al., 2002; Flynn et al., 2005; Leip et al., 2011; Shepherd et al., 2015; Yue et al., 2019) and the IPCC as well (De Klein et al., 2006), indicate that N_2O EF's are influenced by characteristics that are unique to a certain crop and region and that emissions vary spatially and temporally due the differentiation of local management practices and climate conditions (Gerber et al., 2016; Guevara et al., 2019; Wang et al., 2011). Other factors that are dependent on the crop type are the N fertilizer inputs and irrigation applied (Aguilera et al., 2013). According to Brentrup et al. (2000) it is estimated that almost 80% of N_2O emissions from agricultural soils are linked to mineral and organic fertilizers. Fertilizers provide available N to the soil for denitrification and nitrification processes.

Moreover, studies emphasize the importance of precipitation, temperature, and soil climatic factors for the activation of nitrification and denitrification (Corre et al., 1999; Dachraoui and Sombrero, 2020; Dobbie et al., 1999). Rochette et al. (2008) explains how precipitation and high temperatures enhance the soil moisture content, which then increases the water filled pore space in agricultural soils. As moisture fills the soil pores, there is less available oxygen in the soil, promoting conditions for denitrification. Thus, establishing regional EFs that consider these factors can improve direct N_2O emission estimations. The IPCC indicates that a "tier 2" method to calculate direct N_2O emissions should use specific EFs and these correspond to regional EFs for specific conditions (climatic and of cultivation) and N inputs (e.g. for mineral and for organic fertilizers) (De Klein et al., 2006).

Most N_2O emissions estimates exist for the agricultural sector at global level (Tesfaye et al., 2021) or country level, as part of the National Inventory Submissions made to the United Nations Climate Change Convention (UNFCCC) secretariat (UNFCCC, 2015, 1997). Fewer estimations of N_2O emissions have been made for more localized agricultural areas and in concrete for peri-urban agricultural regions i.e. agriculture usually referring to open-air, soil-based, ground-base, conventional agricultural practices around cities (Dorr et al., 2021) – definition also adopted in this study. One of the reasons for this is the lack of finer-scale land cover datasets including relevant information. Most geographically explicit datasets include aggregated typologies of croplands and lack information on agricultural management practices at relevant resolutions, which are vital to answer questions related to biogeochemical cycles (Monfreda et al., 2008), resource circularity and for more accurate greenhouse gas estimations. Moreover, peri-urban agricultural areas are becoming increasingly relevant particularly in the light of pandemics and the most recent COVID-19 crisis (Vittuari et al., 2021), not to mention the imminent climate crisis (IPCC, 2021) as they may increase resilience and sustainability and self-sufficiency of cities' food supply (Langemeyer et al., 2021). Assessing the benefits and costs provided to cities by peri-urban agricultural areas requires appropriate geographically explicit datasets, at relevant resolutions and with relevant information.

In this study we aim to provide a method for more accurate estimation of direct N_2O emissions, building on the creation of a peri-urban agriculture map including irrigation and fertilization information, as well as crop-specific EFs, at an appropriate resolution. We harness the best available data and combine land cover maps, local agricultural statistics (e.g. individual crop type, crop surfaces), management practices (e.g. kg N fertilizer and irrigation applied), a soil map and EFs (i.e. IPCC Tier 1 EF and crops-specific EFs) to obtain a novel peri-urban agriculture map and spatially distributed emissions. We focus in the peri-urban agricultural sector of the Metropolitan Area of Barcelona (AMB for its acronym in Catalan) in Spain where such map and N_2O emissions distribution is not existent, as known to us. We further briefly discuss the usefulness of the outputs on mitigation, sustainability and circularity studies, among others.

2. Methodology

Four basic steps were followed to spatially distribute the direct N_2O emissions of peri-urban agriculture (Fig. 1). First, the study area was defined and data was collected for it, in particular, individual crop management data, and crop-specific emission factors. Second, cropping systems, defined as a single crop with its specific irrigation and fertilizer management, were selected based on the available data. Third, two approaches were used to calculate direct N_2O emissions per crop, 1) the IPCC Tier 1 method (Tier 1) and 2) using crop-specific EFs for selected cropping systems (Tier 2). Finally, calculated emissions are mapped. In this section we describe each step.

2.1. Data collection for cropping systems and study area

The study area for this work is the Metropolitan Area of Barcelona (AMB). AMB is in the North-East region of the Iberian Peninsula and it includes 36 municipalities of the autonomous community of Catalonia in Spain (see Supporting information (SI) 1, Fig. S.1). Peri-urban and urban agriculture are widespread agricultural practices in AMB, although they have decreased in the last 50 years (Rufí-Salís et al., 2019). Scenarios of

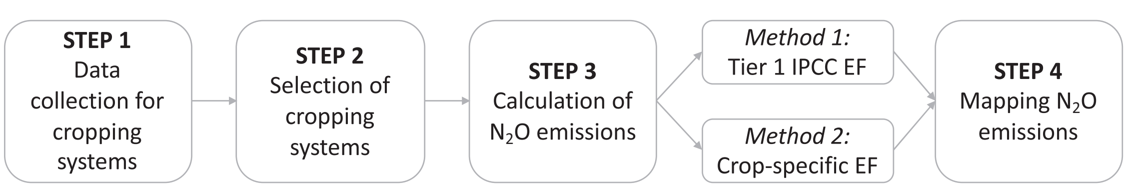


Fig. 1. Methodological steps followed in this study to map peri-urban agricultural direct N_2O emissions for the Metropolitan Area of Barcelona.

urban and peri-urban agricultural expansion within the AMB and its sustainability challenges are explored in the Land Use Master Plan (PDU for its acronym in Catalan) which has green infrastructure as one of the 6 key themes currently under development (Barcelona Regional and AMB-PDU, 2019; Metropolitan Area of Barcelona, 2021). At present, the AMB encompasses 5584 ha of cropland (Fig. 2). The year under assessment is 2015, as it is the year with the most recent Land Cover Map of Catalonia (CREAF, 2015). This map, referred to as the MCSC map, is central to the crops' selection and emissions mapping, as will be further described. It contains a high-resolution thematic cartography of the main types of land cover of the country (forests, crops, urban areas, etc.). Moreover, individual crops are not included in this map, but are described at the level of herbaceous crops, fruits, vineyards, olives, vegetables and greenhouses among other aggregated crop-groups or land use categories.

During the initial collection of data, individual crop management data, and EFs were reviewed. For crop management, the review revealed fewer data at the AMB level, and most available sources reported data at more aggregated regional scales e.g. country (Spain), autonomous community (Catalonia) or provincial (Barcelona) levels. Therefore, data at the Catalonia and Barcelona level was collected. For each level, we recorded the crop types either for individual crops (e.g. wheat) or for crops groups (e.g. cereals) - depending on the availability, their production surface (ha) and yield (kg/ha) (Generalitat de Catalunya, 2016; MAPA, 2016). Moreover, their irrigation type (whether irrigated or rainfed) and annual fertilizer application (kg N year^{-1}) were also recorded (García-Serrano Jiménez et al., 2010; MAPA, 2016; Mercade et al., 2010).

Regarding the EFs, the study by Cayuela et al. (2017) is a key source employed. We use a subset of its meta-analysis (see Section 2.3.2 for details on this calculation) of available measurement data of direct N_2O emissions from Mediterranean cropping systems and the detailed EFs at the individual crop level to further calculate the crop-specific EFs.

2.2. Local activity data

Local activity data corresponds to total annual N fertilizer application estimates per crop (kg N year^{-1}). To calculate these values, as on-site data was not available, we used a bottom-up approach based on the N fertilizer rate per crop (kg N ha^{-1}) and area of each crop plot (see Section 2.4 for the calculation of these areas), following Eq. (1).

$$\begin{aligned}&\text{Annual N fertilizer application per crop}\left(\text{kg N year}^{-1}\right)\\&\quad=\text{Area of individual crop}\left(\text{ha year}^{-1}\right)\\&\qquad\times\text{N fertilizer rate per crop}\left(\text{kg N ha}^{-1}\right)\end{aligned}\tag{1}$$

Three sources of data were used for the N fertilizer rate per crop in Eq. (1): 1) The N requirements per crop reported in the "*Practical guide to the rational use of fertilizers on crops in Spain*" by the Ministry of Agriculture, Fisheries and Food (García-Serrano Jiménez et al., 2010) assuming total N fertilizer application to crops following the crops' requirement of N and is thus applied in an optimal way; 2) the estimation of N fertilizer rate per crop from the HERMESv3, a multiscale atmospheric emission modelling framework (Guevara et al., 2019), for what the model uses data from the Spanish Ministry of Agriculture, Fisheries and Food on surfaces and yield (MAPA, 2015) and the "*Practical guide to the rational use of fertilizers on crops in Spain*" (García-Serrano Jiménez et al., 2010), as well as from Mueller et al. (2012); and 3) for crops not available in the two previous sources, the N fertilizer rate was calculated from the initially collected data at the Catalonia level. For the latter, we use the total annual production and annual surface of the crop to calculate an average annual yield in ton per ha (Generalitat de Catalunya, 2016). Then, the coefficients of N extraction in kg N per ton, was derived from the Nitrogen Balance from the Spanish Government (MAPA, 2016) and by means of these two values the average fertilizer rate per ha was derived (SI 1, Table S.1). Table S.2 in SI 1 shows the values and data sources used for the N fertilizer rate per crop, also shown per crop group in Table 1.

For the crop area values in Eq. (1), a collection of cartographies from the AMB were hybridized (see Section 2.4). Together, fertilizer rate and crop areas, yield a map for annual N fertilizer application per crop (Fig. 3).

2.3. Calculation of N_2O emissions for selected cropping systems

We use two methods to estimate direct N2O emissions according to Eq. (2).

$$\begin{aligned}&\text{Direct N}_2\text{O Emissions}\left(\text{N}_2\text{O}{-}\text{N year}^{-1}\right)\\&\quad=\text{Emission Factor}\ (\text{kg N}_2\text{O}{-}\text{N/kg N})\\&\qquad\times\text{Annual N fertilizer application per crop}\left(\text{kg N year}^{-1}\right)\end{aligned}\tag{2}$$

The methods vary the EFs (Tier 1 and Tier2) and use the map of fertilizer application per crop.

2.3.1. Tier 1: IPCC emission factor

Method 1 follows the IPCC's tier 1 guidelines for estimating direct N_2O emissions from agricultural soils. IPCC's Tier 1 emission factor assumes that 1% of the N applied into the soil will be emitted as direct N_2O emissions (De Klein et al., 2006). Therefore, in Eq. (2), the EF is replaced for 0,01 kg N_2O-N/kg N for all crops and this is multiplied by the estimated annual N fertilizer application per crop to estimate the direct N_2O emissions. The emissions calculated from this method are used as a reference for comparison.

2.3.2. Tier 2: crop-specific emission factors

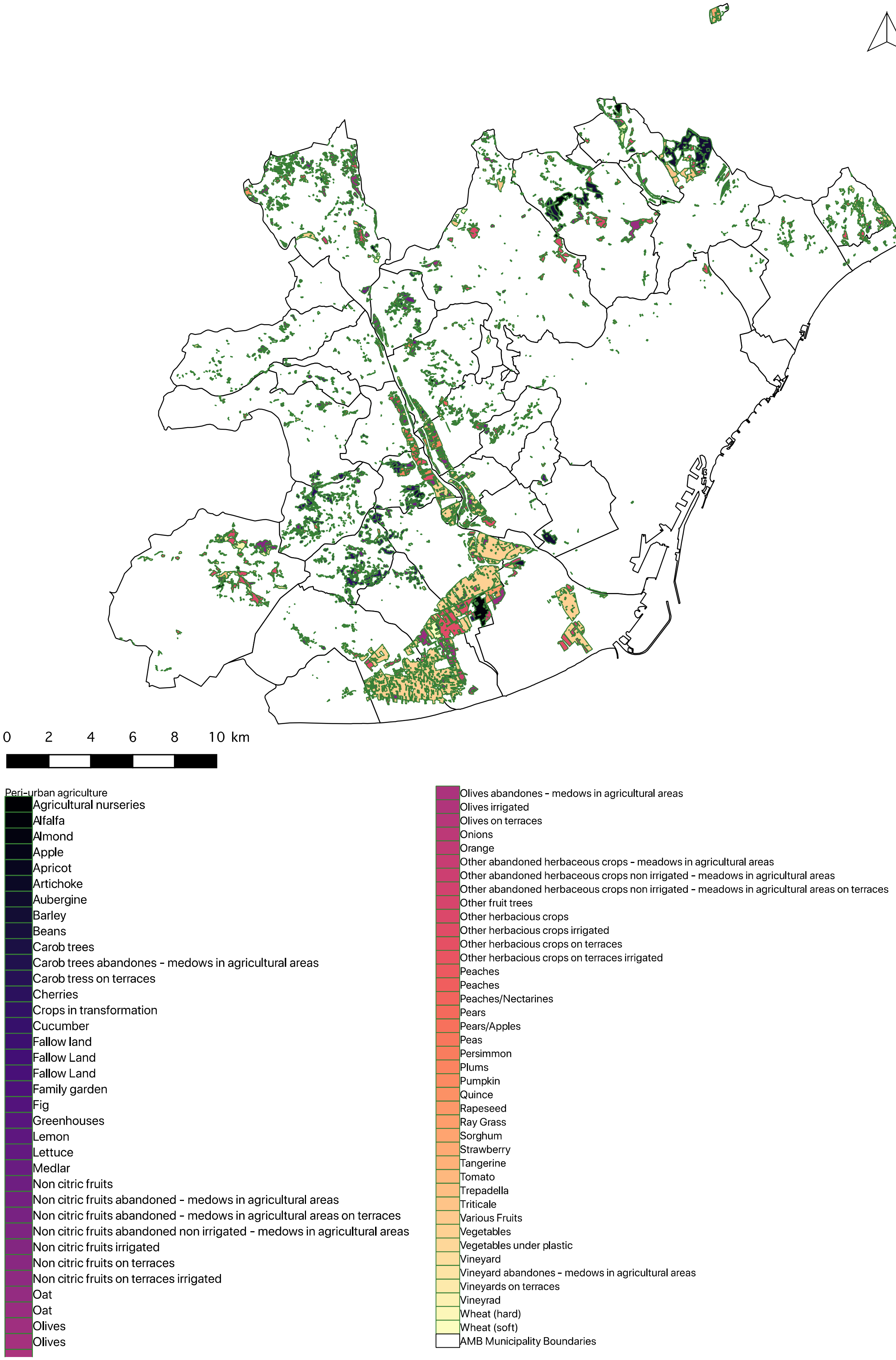
EFs for this method are adapted from the Cayuela et al. (2017) Mediterranean meta-analysis. To fit the area of this study, the meta-analysis was refined by excluding case studies of used inhibitors and rice crops, because they are not representative for the AMB, and by adding cases from Pi and Deng (2019), that provide additional N_2O estimations for cropping systems of interest in the AMB, particularly the Fruit crops. As a result, 22 case studies and 93 different N_2O EFs were included, 12 of these case studies are from Spain, and the rest are from Australia, Chile, Italy, and the USA. Using SPSS statistical analysis software, new mean EFs are established based on the following conditions: crop type, irrigation type (irrigated or rainfed) and fertilizer type (mineral or organic) and fertilizer application rate (kg N ha^{-1}). We refer to these EFs as crop-specific EFs (SI 1, Table S.2), also shown in Table 1 per crop group. The SI 2 supplies the meta-analysis subset where crop-specific EFs as well as crop group EFs are derived. The latter were applied to individual crops lacking crop-specific EFs for the area of study. For example, the meta-analysis provided EFs for oat, however, because the rainfed EFs in the meta-analysis only has one literature source, the specific crop EF based on this source was not used. Instead, the cereal crop group of 0.0029 kg N_2O-N/kg N was applied.

2.4. Mapping N_2O emissions

2.4.1. Crop areas

This section describes the methodology for creating the crop map for our study region. For this purpose, two maps have been used. First, the DUN-SIGPAC (as we refer to it in this study) is a map provided by the Department of Agriculture, Livestock, Fisheries and Food from the Generalitat de Catalunya (DARPA, 2015) containing the annual declaration of crops (Declaració agrària, DUN) made by farmers in Catalonia, which matches the public registry of Geographic Information System of agricultural parcels in Catalonia (Sistema d'informació geogràfica de parcel·les agrícoles, SIGPAC for its acronym in Catalan). This map contains very detailed but incomplete information on the province, district, municipality, crop-group, individual crops and whether they are irrigated, on an annual basis. Second, the MCSC map (CREAF, 2015) contains less detail on agricultural parcels, but has more spatially complete information.

These two maps have been hybridized into one containing the detail of DUN-SIGPAC map and the spatial completeness of MCSC map, by means of the generalization of the DUN-SIGPAC crop information as follows. The first step was to apply the Voronoi diagram or Thyssen polygons (Gold


0 2 4 6 8 10 km
Peri-urban agriculture
Agricultural nurseries
Alfalfa
Almond
Apple
Apricot
Artichoke
Aubergine
Barley
Beans
Carob trees
Carob trees abandones - medows in agricultural areas
Carob tress on terraces
Cherries
Crops in transformation
Cucumber
Fallow land
Fallow Land
Fallow Land
Family garden
Fig
Greenhouses
Lemon
Lettuce
Medlar
Non citric fruits
Non citric fruits abandoned - medows in agricultural areas
Non citric fruits abandoned - medows in agricultural areas on terraces
Non citric fruits abandoned non irrigated - medows in agricultural areas
Non citric fruits irrigated
Non citric fruits on terraces
Non citric fruits on terraces irrigated
Oat
Oat
Olives
Olives
Olives abandones - medows in agricultural areas
Olives irrigated
Olives on terraces
Onions
Orange
Other abandoned herbaceous crops - meadows in agricultural areas
Other abandoned herbaceous crops non irrigated - meadows in agricultural areas
Other abandoned herbaceous crops non irrigated - meadows in agricultural areas on terraces
Other fruit trees
Other herbacious crops
Other herbacious crops irrigated
Other herbacious crops on terraces
Other herbacious crops on terraces irrigated
Peaches
Peaches
Peaches/Nectarines
Pears
Pears/Apples
Peas
Persimmon
Plums
Pumpkin
Quince
Rapeseed
Ray Grass
Sorghum
Strawberry
Tangerine
Tomato
Trepadella
Triticale
Various Fruits
Vegetables
Vegetables under plastic
Vineyard
Vineyard abandones - medows in agricultural areas
Vineyards on terraces
Vineyrad
Wheat (hard)
Wheat (soft)
AMB Municipality Boundaries

and Angel, 2006) on the DUN-SIGPAG polygons. This methodology divides the plane into regions represented by a polygon with a center point for each region. For each center point the closest region values are assigned. This procedure generates the Voronoi polygons, with DUN-SIGPAC information associated. The next step is the validation of the associated information to each of the polygons by means of a Python code. This code contains a dictionary that relates the crop categories of both maps, having more specific categories for the DUN-SIGPAC map with respect to those of the MCSC. For instance, the typology Citrus Fruits in MCSC map relates to Lemon, Mandarin, Orange and other Citrus in the DUN-SIGPAC map typologies. The code checks if there is a match between DUN-SIGPAC and MCSC land cover typologies. When the two categories coincide i.e. belong to similar descriptions e.g. Mandarine for DUN-SIGPAC and Citrus Fruits for MCSC, a positive result is obtained. We have positive results in about 40% of the polygons, where the DUN-SIGPAC information is used. To avoid the mismatch of the 60% remaining i.e. where the more detailed DUN-SIGPAC and more generic MCSC crop typologies do not match (due to differences in the source of information) the more generic typology associated with the MCSC map is used.

Data from two sources has been used for the irrigation method per crop and polygon i.e. irrigated or rainfed. First, cadastral cartography data (Dirección General del catastro, 2014) has been integrated onto the MCSC map repeating the Voronoi polygons methodology previously described, assigning irrigation/no irrigation to each polygon. The second source is the MCSC map itself that classifies land under irrigated or non-irrigated. For both sources, a similar number of polygons are irrigated i.e. 52.6% according to Cadastral data and 54,25% according to MCSC map.

Finally, information about the municipality in which each MCSC map polygon is located is added to the resulting map. To do this, municipal boundaries (Institut Cartogràfic i Geològic de Catalunya, 2020) have been used. A division has been applied to polygons situated in more than one municipality, resulting in a map with more derived polygons but with municipal information for each of them.

A more detailed explanation of the workflow used to generate the hybrid map is provided in the SI 1 (Fig. S.2). To summarize, the resulting vector map (from now on referred to as the URBAG AMB map since it is fruit of the ERC-Consolidator project Integrated System Analysis of Urban Vegetation and Agriculture, URBAG) includes the following information associated to each polygon: the crop type according to the Voronoi methodology and further dictionary check (Fig. 2), irrigation according to MCSC and Cadaster data (SI 1, Figs. S.3, S.4) and its municipality (SI 1, Fig. S.1). From this map we derive the area per crop used in Eq. (1) to determine the total fertilizer input per crop area (the individual polygons).

The URBAG AMB map also provides data on the irrigation method used per crop area, in order to assign the right crop-specific EFs when applying Tier 2 method to estimate direct N_2O emissions, for which the MCSC irrigation data is used. The largest crop groups in the URBAG AMB map, including irrigated and rainfed areas, are the cereals, vegetables and non-citric fruits with a share of 36, 33 and 23% respectively, of the total peri-urban areas in the AMB (Table 1). The map attributes are described in the SI 1, and the shape file is also provided in SI 3.

2.4.2. Calculation of spatial emissions for Tier 1 and 2 methods

The local activity data was also integrated into the attribute table of the URBAG map. Specifically, the annual N fertilizer application per crop in kilograms, according to Eq. (1), the IPCC Tier 1 EF, and the crop-specific EFs were integrated for each polygon. This creates more detailed attribute tables which enables the calculation of direct N_2O emissions at a polygon level using Eq. (2). As a result, two direct N_2O emission maps are created and compared. One map shows the IPCC tier 1 emissions, and the second shows crop-specific emissions.

2.4.3. Qualitative component: soil map

The effect of soil characteristics on EFs was not quantified. We, however, add a soil map layer with qualitative information to as why emissions are higher in certain areas compared to others. The Institut Cartografic i Geologic de Catalunya (ICGC) provides the Catalonia soil map (Mapa de sòls de Catalunya) (ICGC, 2018), that uses the international World Reference Base classification system (see Fig. S.5). This layer enables the description of influencing factors such as climatic factors on quantified emissions in the AMB. Most of the peri-urban agriculture in the AMB fall within *Calcaric Fluvisol*, *Fluvic Arenosol* and *Eutri Leptosol* soils.

3. Results

This section displays the results of each step completed to calculate direct N_2O emission maps.

First, Fig. 3 panel A, shows the raster map for the annual N fertilizer applications at a 100 × 100 meter resolution for the AMB. Fig. 3 panel B, shows the vector map with the crop-specific EFs per parcel on the URBAG map.

3.1. Tier 1 N_2O emissions

The IPCC Tier 1 EF assumes that 1% of the fertilizer applied to a crop is released to the air as N_2O. Thus, emissions in Fig. 4 (left map) correlate linearly with the N fertilizer input i.e. emissions are higher for parcels with higher N fertilizer inputs and vice versa. Because this method does not recognize local climatic factors, management practices nor crop type, emissions produced in this map are a rough estimation for the AMB and are meant to serve as a first reference level of data for this study. Total direct N_2O emissions for peri-urban agriculture in the AMB based on the Tier 1 method are 7718 kg N_2O-N year^{-1} i.e. 12.12 tons of N_2O year^{-1}, which using a global warming potential of 298 kg CO_2eq per kg N_2O according to the IPCC Fifth Assessment Report leads to 3611 tons CO_2eq year^{-1}.

3.2. Tier 2: crop-specific emission factors

Fig. 4 (right map) shows the direct emissions considering the Tier 2 crop-specific EFs. Because the EFs come from studies applying similar agricultural practices, for example, whether crops are rainfed or irrigated, and uses both mineral and organic fertilizer, these emissions are expected to be more accurate than those estimated under Tier 1. Total direct N_2O emissions for peri-urban agriculture in the AMB based on the Tier 2 method are 6533 kg N_2O-N year^{-1} i.e. 10.25 tons of N_2O year^{-1}, which using a global warming potential of 298 kg CO_2eq per kg N_2O according to the IPCC Fifth Assessment Report leads to 3056 tons CO_2eq year^{-1}.

4. Discussion

4.1. Differences between Tier 1 and Tier 2 methods

Overall, the IPCC's default value of 0.01 kg N_2O-N/kg N is higher than the crop-specific EFs for some crops e.g. Sorghum, Barley, Wheat, Oat, Triticale, Olive, and Almond and lower for others e.g. Cucumber, Tomato, and Vineyard crops. The lower values of the crop-specific EFs, especially for rainfed crops, leads to lower emissions compared with IPCC tier 1 default EF estimates and the higher values of the crop-specific EFs, for irrigated crops, leads to higher emissions, compared with IPCC tier 1 default EF estimates.

Some selected examples for key crops illustrate these observations. For instance oats encompass 249 ha in the AMB and emit 292 kg N_2O-N year^{-1} as estimated with Tier 1 CF while using the crop-specific EF lead to 94 kg

Fig. 2. Crop areas in the Metropolitan Area of Barcelona according to the URBAG map, used as the base for determining N_2O emissions. Total areas match the 2015 Land Cover Map of Catalonia (MCSC) by the Centre de Recerca Ecològica i Aplicacions Forestals (CREAF, 2015) and added detailed crop areas correspond to DUN-SIGPAC map (DARPA, 2015).

Table 1
Crop group areas according to the URBAG map, fertilizer rate and emission factors.

Crop group (Catalan)	Crop group (English)	Area (ha)	Share	Emission factor (kg N_2O-N/kg N)	Fertilizer rate (kg N ha^{-1})
Cereals	Cereals	2024	36%	0,0029	167,9
Horticoles	Vegetables	1868	33%	0,0148	165,7
Fruita Dolça	Non-Citric fruits	1272	23%	0,0038	61,8
Vinya	Vineyard	131	2,3%	0,0152	59,6
Guaret	Fallow Land	80	1,4%	0	0
Oliverar	Olives	56	1,0%	0,001	57,6
Citrics	Citrics	3	0,05%	0,0028	–[a]
Altres Usos	Other uses	150	2,7%	SI 1, Table S.2	SI 1, Table S.2
Total	Total	5584	100%	–	–

[a] No citric crop group in the URBAG map.

N_2O-N year^{-1}. Also, for all other cereal crops N_2O emissions are larger for Tier 1 than for Tier 2 e.g. Barley (Tier 1: 568 kg N_2O-N year^{-1}; Tier 2: 160 kg N_2O-N year^{-1}), Wheat (Tier 1: 103 kg N_2O-N year^{-1}; Tier 2: 34.2 kg N_2O-N year^{-1}), and Triticale (Tier 1: 125.2 kg N_2O-N year^{-1}; Tier 2: 36.3 N_2O-N year^{-1}), as well as Almond (Tier 1: 5.4 kg N_2O-N year^{-1}; Tier 2: 1.7 kg N_2O-N year^{-1}) and Olive perennial crops (Tier 1: 32.4 kg N_2O-N year^{-1}; Tier 2: 3.2 kg N_2O-N year^{-1}).

Horticultural crops makeup 1868 ha in the AMB – all irrigated, and is the second largest land cover group. IPCC tier 1 method leads to 3098 kg N_2O-N year^{-1}, while crop specific EFs leads to 4588 kg N_2O-N year^{-1}. Vegetables represent 40% of total emissions estimated with Tier 1 CF and 70% of total emissions estimated with crop-specific CFs (See Table S.3 and Fig. S.6 for results per crop group).

Direct N_2O emissions from irrigated vineyard crops are also lower according to the IPCC Tier 1 EF (Tier 1: 0.56 kg N_2O-N year^{-1}; Tier 2: 0.86 kg N_2O-N year^{-1}). According to the 2016 Spanish Nitrogen Balance, for the year of 2016 Vineyards only received organic fertilization (MAPA, 2016) and according to the "*Practical guide to the rational use of fertilizers on crops in Spain*" (García-Serrano Jiménez et al., 2010), the recommended fertilization rate is below 100 kg N ha^{-1} i.e. according to our own calculation 59.6 kg N ha^{-1}. Applying a crop-specific EF that considers this fertilization practice, results in higher emissions compared to the IPCC Tier 1 EF.

Fig. 5 shows the difference between the emissions per year estimated with tier 1 and tier 2 emissions factors (see Table S.3 and Fig. S.6, for results per crop group). Tier 1 leads to 15% more emissions than Tier 2. The general trend shows larger emissions estimated for irrigated horticulture crops and rainfed vineyards with Tier 2 EFs, while for rainfed herbaceous crops, olives and non-citric fruits fewer emissions are estimated with these EFs in comparison with IPCC tier 1 EF.

4.2. Mapping emissions: variability and uncertainty factors

Direct N_2O emissions are sensitive to local crop management practices of irrigation and fertilization, among the most important, and climatic factors, which vary both spatially and temporally. Spatially resolving the emissions with the help of GIS, aids to account for key spatial variability factors. For instance, by including site-specific characteristics of irrigation and fertilization according to the crops grown in the AMB, the bottom-up approach used in this study helps to display the spatial variability of N_2O emissions due to these factors. Also, a regional more accurate estimation of direct N_2O emissions is possible by making geographically explicit such variable factors.

Regarding temporal variability, crop management and climatic factors are also variable. Seasonal changes of these factors should be considered. We used the average yearly input of fertilizers and the irrigation method but the seasonal fertilizers and water used e.g. along a year, could be more accurate and tackle temporal variability of emissions. Such temporal considerations can be accounted for in a geographically explicit manner too, and added on top of the spatial considerations already included here.

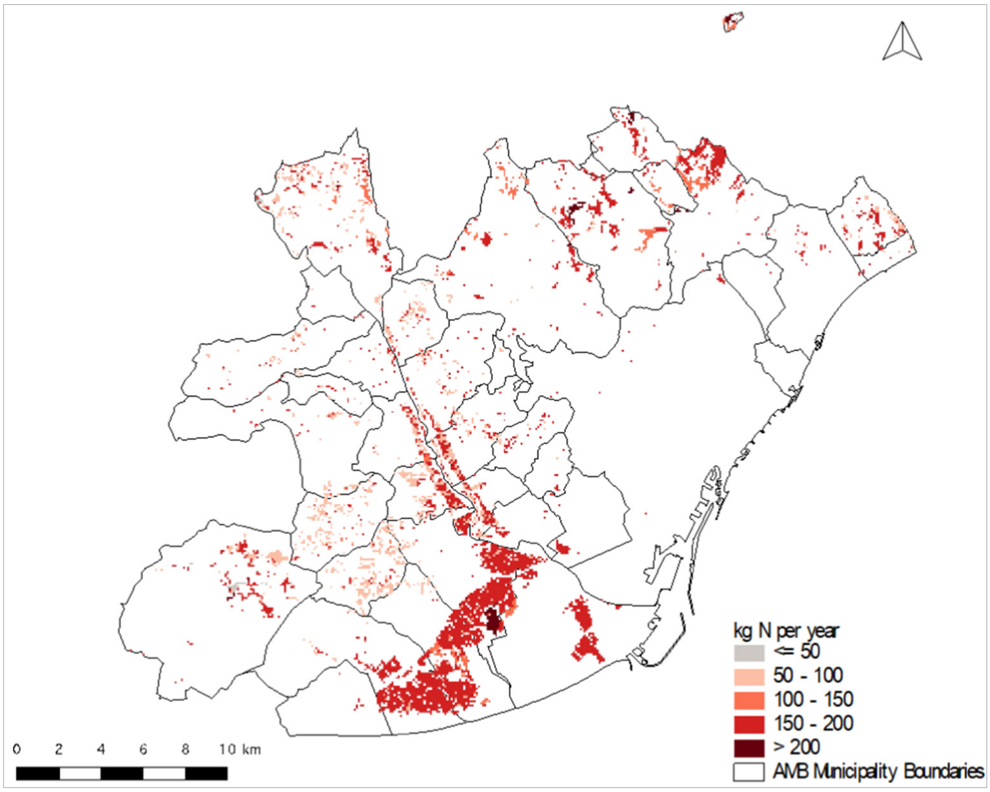
There are also large uncertainties around the results presented here too. Activity data was obtained from data at aggregated geographic levels of Catalonia or Barcelona province. This meant that using these data or downscaled data to represent the AMB level practices, introduced uncertainty due to geographic representativeness. Accuracy is lost when mapping the N fertilizer rate per crop. Crop-specific CFs, are based on field data, for which accuracy is expected to be better. However, despite of data being relevant for the AMB peri-urban agriculture systems, regions outside of the AMB are included. Therefore, some uncertainty remains.

Such uncertainties call for caution in the use of the N fertilizer rate maps and N_2O emission maps i.e. values are indicative, until calibration and verification are undertaken. We nonetheless, believe the developed maps give the order of magnitude of what can be expected on the field including key variability aspects and despite geographic uncertainty of some activity data, they are valuable for other modelling purposes (see Section 4.4). Future work should focus on improving data gaps by conducting on-site surveys with local farmers and applying other participatory approaches on key peri-urban agriculture core areas or gathering field measurements for emissions were possible. Given the large variability in crop management practices, capturing it with field campaigns requires careful design of the campaigns e.g. including measurements over a long enough period of time such a year. Ideally the whole N cycle could be monitored opening a window to the assessment of all N-related inputs e.g. including organic fertilizers and outputs e.g. including other N-related emissions, as well as opportunities to create a more circular peri-urban agriculture sector. Besides, such on-site data could help to assess to what extent downscaling or using data for larger geographic scales introduces uncertainty to the estimated emission inventories.

4.3. The role of crop management and soil types in N_2O emissions

Following the World Reference Base International Soils Classification, the highest direct N_2O from horticulture crops in the AMB came from *Calcaric Fluvisol i Fluvic Arenosol* soils. According to the Soil Atlas of Europe, *Calcaric* soils are composed from calcium carbonate build up and cover many areas in Spain (JRC, 2005). *Fluvisols* are also common soils in European Mediterranean regions and are often areas growing vegetables. This type of soil is often found near rivers, for example, in alluvial basins of Spain such as the Baix Llobregat, the region with the most area of horticulture within the AMB (see Fig. S.5). Collectively, horticultural crops produced the highest emissions in the area of study according to Tier 2. For the year of 2015, our estimates show the AMB emitted 3098 kg N_2O-N year^{-1} (via Tier 1) and 4587 kg N_2O-N year^{-1} (via Tier 2) from horticultural crops growth. Ultimately, higher direct N_2O emissions could be linked to denitrification due to intense management practices and climate characteristics in Baix Llobregat. In the summer, Mediterranean agricultural systems experience intensified management practices due to warmer temperatures and a lack of rain during this time (Aguilera et al., 2013). According to the Idescat (2015) meteorology report, in 2015 the Baix Llobregat region experienced an annual average temperature of 16.6 °C and an annual mean rainfall of 276.6 mm for the year. In terms of irrigation practices, the Baix Llobregat region contains the greatest number of irrigated crops in the AMB. Lettuce and artichoke, typical crops grown in the Agrarian Park of Baix Llobregat, use furrow irrigation as a common practice, and have been found to be over irrigated (Aljoumani, 2012). Similarly, Serra et al. (2016) found poor efficient irrigation practices in the Agrarian park of Baix Llobregat, with only 26.4% of water applied contributing towards irrigated crops. Furthermore, "Estanyar" is a traditional agricultural practice in the Agrarian park of Baix Llobregat, where fields are flooded to wash away salt in the soil (Serra et al., 2018). Generally, using intensive irrigation/flooding practices increases the moisture content in agricultural soils and thus promotes the formation of N_2O emissions. Regarding fertilizer management, horticulture had the second greatest fertilizer inputs as estimated in this study, totaling 310 tons N year^{-1}, after cereals with 324 tons N year^{-1} as input. Mediterranean agricultural soils have experienced an increased amount of over-fertilization (Peñuelas et al., 2013) where high soil nitrate near intensive agricultural areas have been linked to chemical fertilizers, as well as denitrification linked to nitrate from

A.



B.

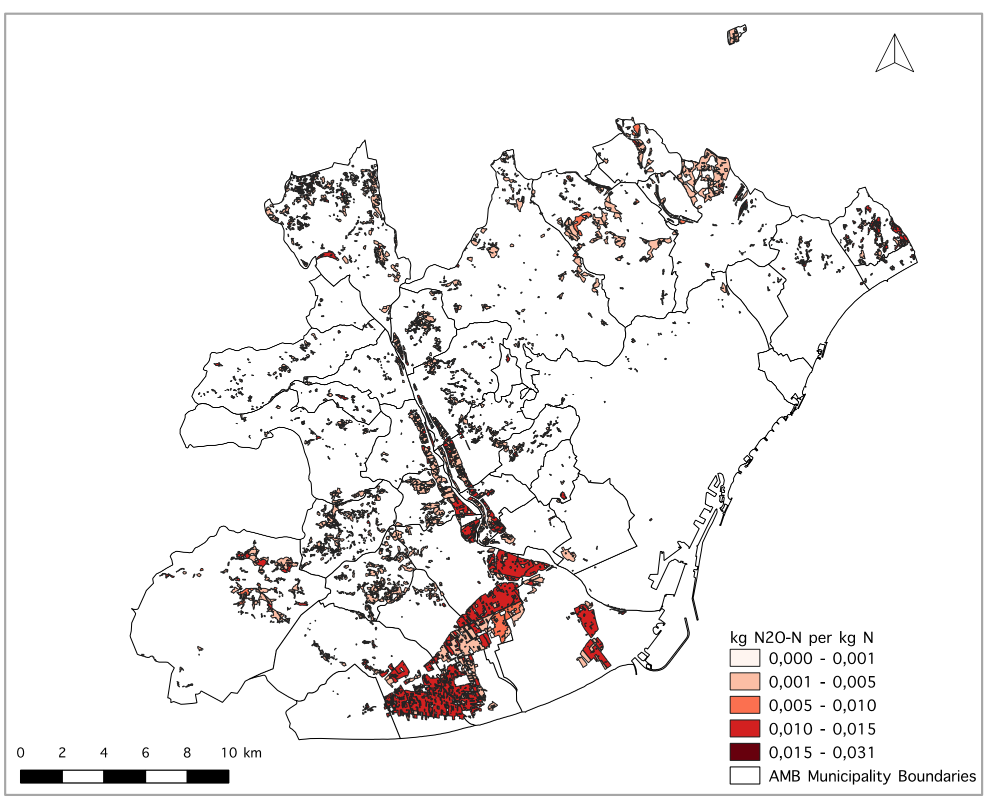


Fig. 3. A) Annual N fertilizer application for peri-urban agricultural in the Metropolitan Area of Barcelona, raster map 100 × 100 meter resolution. B) Crop-specific emission factors for peri-urban agriculture in the Metropolitan Area of Barcelona as estimated based on Cayuela et al. (2017).

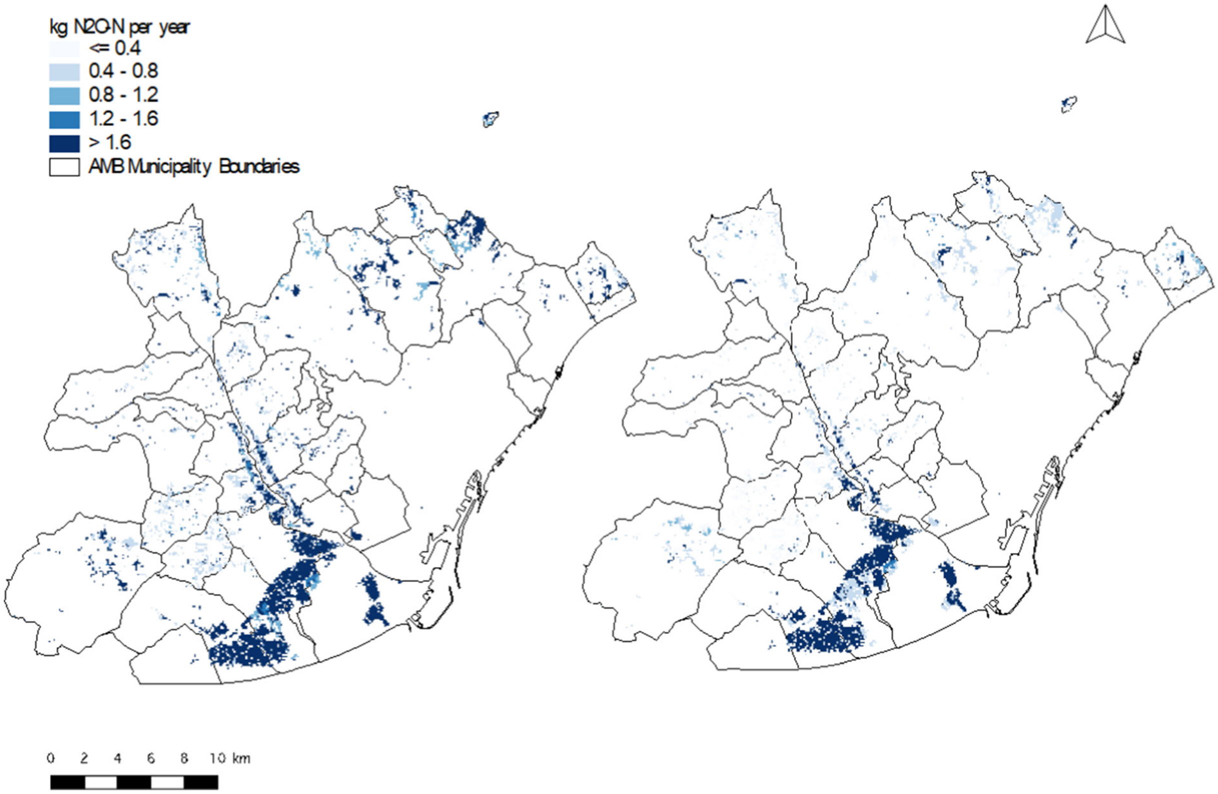


Fig. 4. Direct N_2O-N emissions estimated with the Tier 1 (left map) and Tier 2 (right map) emission factors for peri-urban agriculture in the Metropolitan Area of Barcelona, raster maps 100 × 100 meter resolution.

organic and inorganic fertilizers (Postigo et al., 2021). High emissions of horticultural crops in Baix Llobregat could be related to the high N inputs leading to nitrate in the soil and the high irrigation inputs limiting oxygen availability due to water flowing into the soil pores instead. Thus, under wet soils, and warm temperatures (16.6 °C) anaerobic conditions are promoted. This activates microbial activity for denitrification. More specifically, the microbes breakdown the nitrate in the soil and produce direct N_2O along the process.

The highest direct N_2O emissions from cereal crops in the AMB came from *Calcaric Cambisol I Haplic Calcisol* soils. According to the Soil Atlas of Europe, *Cambisols* are deep, productive soils in Southern Europe and are primarily used to produce food/oil in Mediterranean regions (JRC, 2005). For the AMB, over half of the cereals were produced in the Vallès Occidental region. Total cereals cultivation in the AMB covered 2024 ha and emitted 3237 kg N_2O-N year^{-1} (via Tier 1) and 1050 kg N_2O-N year^{-1} (via Tier 2). About 73% of the cereal areas in the AMB are rainfed and 27% are irrigated, according to the URBAG map. Idescat (2015) meteorology report, shows the Vallès Occidental region experienced an annual average temperature of 15.5 °C and an annual mean rainfall of 326.6 mm. Emissions from cereal crops were found to be much lower than those of horticultural crops, all irrigated. This could be related to the temperature, irrigation practice, and fertilizer differences. Barton et al. (2008) showed that direct N_2O emissions are sensible to seasonal changes in temperature and rainfall. For example, in a rainfed system there is not as much water flowing into the pores of agricultural soils, allowing space for available oxygen. Along with colder temperatures, these conditions are unsuitable for denitrification. Furthermore, these conditions make nitrification the primary process for direct N_2O production (Aguilera et al., 2013).

4.4. Implications for food sovereignty and sustainable peri-urban crop production

N_2O emissions maps of peri-urban agriculture activity, as we propose in this study, are a key piece for an appropriate introduction of mitigation, sustainability and circularity strategies. For instance, overly irrigated or fertilized peri-urban agriculture areas will benefit from strategies such as crop diversification, reduction of overfertilization, optimal water management, alternative fertilization methods - such as inoculants (Arcas-Pilz et al., 2021), nutrients recirculation (Rufí-Salís et al., 2020), etc. Moreover, spatially distributing all nitrogen flows i.e. not only N_2O emissions, is essential knowledge to apply strategies in appropriate areas and thus is essential for sustainable local food production. N_2O emission maps, together with the fertilizer use maps developed in this study, are already two key pieces of the full N-Cycle for the city local food production, which should cover all N flows to air, water, soil and crops. Moreover, reducing N_2O emissions from peri-urban agriculture, by for instance managing crop type, fertilization and irrigation in relation to soil type, also contribute to climate change mitigation.

Expansion scenarios of peri-urban agricultural areas, as proposed by the PDU of the AMB (Barcelona Regional and AMB-PDU, 2019), show that restoring agricultural areas lost in the past helps mitigate negative socioecological impacts by increasing diversity of ecosystem services e.g. food security and reducing reliance on imports (Padró et al., 2020). Therefore, appropriate management of new peri-urban agricultural areas could bring along these advantages and generate synergies between peri-urban agriculture and environmental services such as climate change mitigation. The way we calculate emissions and maps estimated here, may be used in conjunction with other methods e.g. life cycle assessment and environmental risk assessment for broader sustainability assessments of for instance, the PDU scenarios of expansion of peri-urban agriculture areas and the sustainability challenges brought by the expansion.

5. Conclusions

This study presents improved direct N_2O emissions maps from peri-urban agriculture in the Metropolitan Area of Barcelona (AMB). We recommended using crop-specific EFs when calculating direct N_2O emissions at

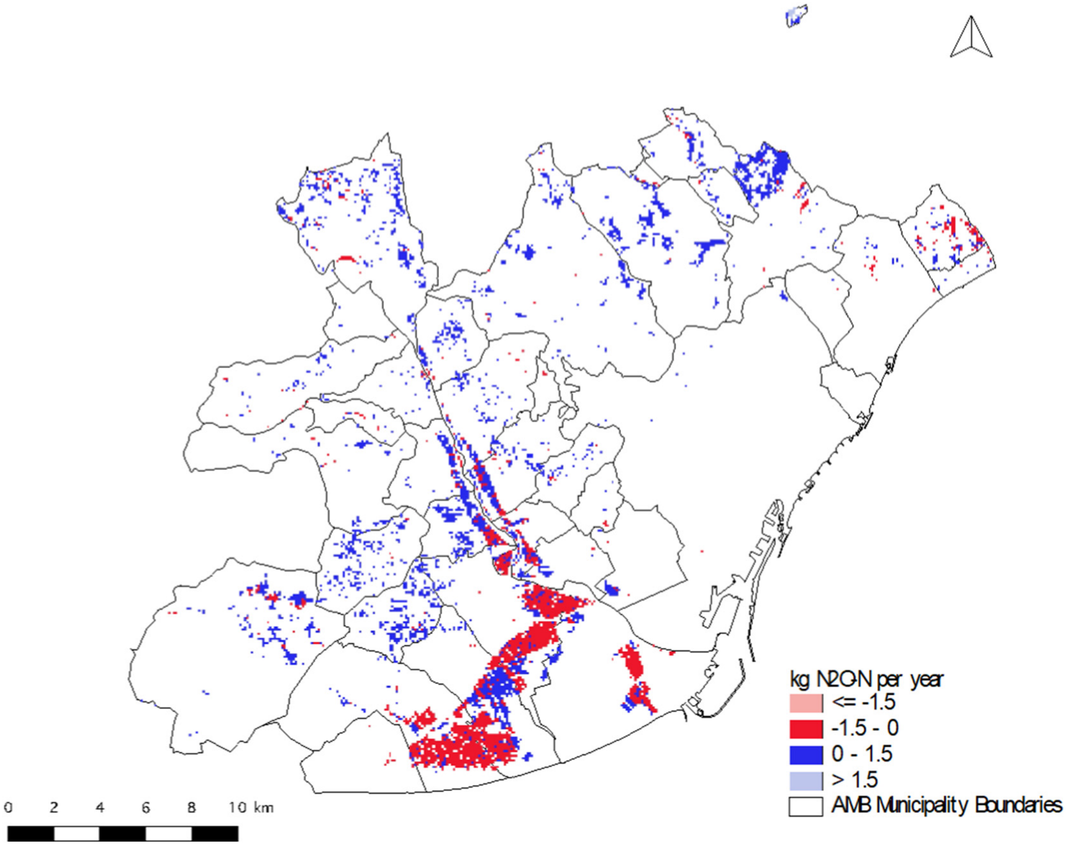


Fig. 5. Difference between emissions calculated with Tier 1 and Tier 2 emission factors, 100 × 100 meter resolution map.

finer scales – such as those of peri-urban agriculture, because they capture variability of crop management practices such as fertilization and irrigation, relevant for the quantification of these emissions. Applying crop-specific EFs and mapping emissions enables visualization of key emitting core areas and helps highlight appropriate strategies for their further mitigation. As a result, two core areas of emissions in the AMB were observed: the Baix Llobregat and Vallès Occidental regions. Overirrigation to crops may influence emissions especially in the Baix Llobregat region, and over fertilization also influence emissions in both of these areas where irrigated vegetables and rainfed cereals dominate, according to our improved agricultural land use map. Results show that Tier 1 leads to lower emissions for irrigated crops compared to crop-specific EFs, while it leads to higher emissions for rainfed crops, highlighting the need to account for local parameters while quantifying N_2O emissions in regional studies.

This study's data and method to map and estimate direct N_2O emissions can be further applied to areas beyond peri-urban agriculture areas as long as the cultivation techniques are similar to those of conventional agriculture, as defined here i.e. open-air, soil-based, ground-base, conventional agricultural practices. For the case of organic, hydroponic or other hi-tech urban agriculture, emission factors and fertilizer rates do not hold, and should be updated despite that similar mapping and estimation of emissions could be used.

Ideally, spatially distributing all nitrogen flows i.e. all inputs (including organic fertilization) and outputs (including all N-related emissions), could help identify new opportunities to increase the circularity of the sector, apply appropriate strategies towards sustainability and mitigate climate change. For instance, optimizing the use of fertilizers and irrigation for the peri-urban agriculture in the AMB, can actively contribute to the mitigation of N_2O emissions and thus contribute as a strategy for climate change mitigation and help tackle the current climate crisis, besides the importance of the local food supplied to the city from these areas that are actively contributing to the AMB self-sufficiency and its resilience capacity, all objectives of the PDU.

On-site data of crop management practices could help overcome uncertainties introduced due to data representativeness in this study. More detailed climate dependant EFs, that reflects the soil and water influence on N_2O emissions generation, which are qualitatively accounted for in this study, could help improve further the EFs used here. Mapping efforts that incorporate local data of water management and soil characteristics can also allow for indirect N_2O emissions to be estimated. Furthermore, this case study provides rough estimations of N_2O emissions for the AMB and should be seen as a point of reference i.e. a first picture, to further build upon more robust emission inventories and improved EFs also accounting for temporal variability of climate and crop management practices.

CRediT authorship contribution statement

Conceptualization: AMB, KJ, GV. Data collection: AMB, KJ, SV, CML. Data analysis: AMB, KJ, MRS. Visualizations: AMB, KJ. Writing, review and editing of manuscript: AMB, KJ, MRS, SV, CML, GV. Supervision: GV.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153514.

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